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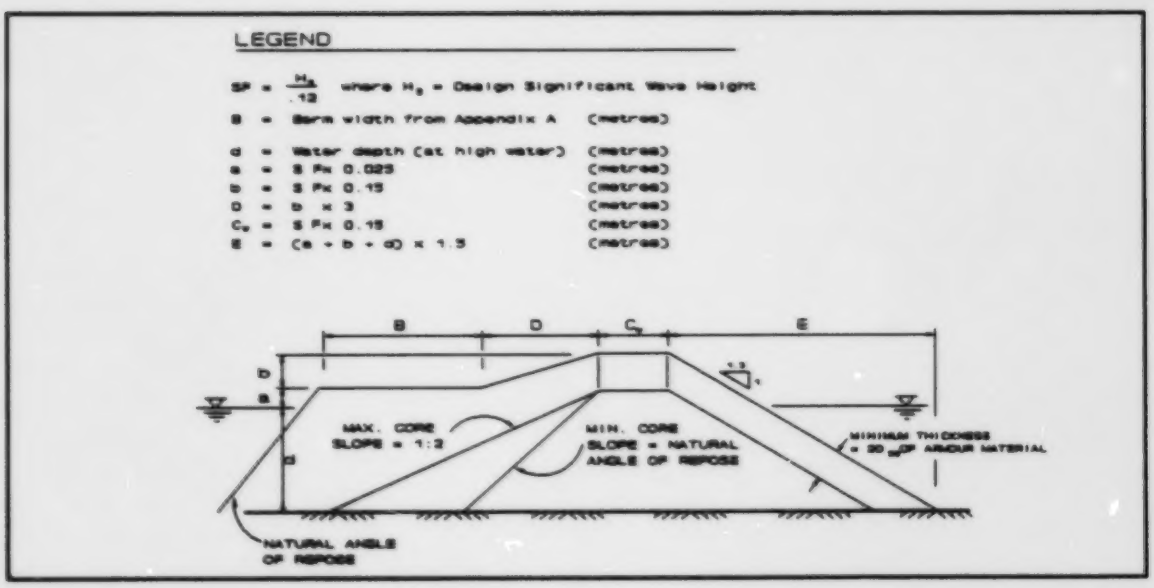
SMALL CRAFT HARBOUR BRANCH
DEPARTMENT OF FISHERIES AND OCEANS

A STUDY OF THE STABILITY OF BERM BREAKWATERS

DESIGN GUIDELINES


LEGEND
SF = Hs/.12 where Hs = Design Significant Wave Height
B = Berm width from Appendix A (metres)
d = Water depth (at high water) (metres)
a = S Fx 0.025 (metres)
b = S Fx 0.15 (metres)
D = b x 3 (metres)
Cy = S Fx 0.15 (metres)
E = (a + b + d) x 1.5 (metres)
B
D
Cy
E
MAX. CORE SLOPE = 1:2
MIN. CORE SLOPE = NATURAL ANGLE OF REPOSE
NATURAL ANGLE OF REPOSE

OCTOBER, 1991

REPORT # 2 - DESIGN GUIDELINES

A STUDY OF THE STABILITY OF BERM BREAKWATERS

SMALL CRAFT HARBOURS BRANCH
DEPARTMENT OF FISHERIES AND OCEANS

OCTOBER, 1991

BY DR. K.R. HALL

QUEEN'S UNIVERSITY COASTAL ENGINEERING LABORATORY

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FOREWARD

This report puts forward guidelines for the preliminary design of dynamically stable or berm type breakwaters. These guidelines have been based on the results of an extensive series of hydraulic model tests as carried out over a two year period at the Hydraulic Model Laboratory of Queen's University at Kingston. Funding support for this study was provided by the Small Craft Harbours Branch of the Department of Fisheries and Oceans and the now defunct unsolicited proposal fund of Supply and Services Canada.

The purpose of this study was to identify the major variables involved in the design of dynamically stable breakwaters and to provide a procedure whereby an engineer could determine the general dimensions of the structure based on local wave conditions and characteristics (size and yield) of local quarries. Once the overall feasibility of such a structure is determined, the final design can be prepared either with in-house expertise or through the services of a professional with the requisite expertise and experience in berm breakwater design. This will generally involve a physical model study and careful consideration of the long term durability of the stone.

This study has been completed under the general direction of a steering committee who gave freely of their time and expertise to assure the technical quality of this document. This committee consisted of:

W.F. Baird	W.F. Baird and Associates
C. Glodowski	Public Works Canada
Dr. E. Mansard	National Research Council
M.W. Mulcahy	Department of Fisheries and Oceans

It is the opinion of the steering committee that these design guidelines contain the most complete information available today to determine the physical dimensions of dynamically stable breakwaters. As this field is constantly changing due to ongoing research and prototype experience, these design guidelines should not be considered as final and should be revised and updated as future developments dictate.

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1.0 INTRODUCTION

This report presents guidelines for producing a design of a berm breakwater. Depending upon the quality of the design criteria, the complexity of the site and other limitations discussed later in this report, the level of confidence in this design will vary such that the design may be suitable for preliminary volume and cost estimates or, in some instances, as a final design.

The guidelines were developed based on the results of a research programme undertaken by the Small Craft Harbours Branch of the Department of Fisheries and Oceans in conjunction with the Queen's University Coastal Engineering Research Laboratory (QCERL). The study, which was directed at producing a set of guidelines for the design of naturally armouring or berm breakwaters and shore protection structure was completed under Supply and Services Canada File Number 055FF.FP802-8-2824 and Contract Number FP802-2824/01-SS. Mr. M. Mulchahy, Director of Harbour Maintenance, SCH, was the acting scientific authority for the client.

The investigation at QCERL was undertaken by graduate students in the Department of Civil Engineering at Queen's University under the supervision of Dr. K.R. Hall.

The report is intended only to provide information required by the designer. Support data and full documentation of the test programme leading to the design information presented in this guideline can be found in "Report # 1 - Hydraulic Model Tests - A Study of the Stability of Berm Breakwaters", hereafter referred to as Report # 1.

2.0 DESIGN PHILOSOPHY

2.1 WHAT ARE BERM BREAKWATERS?

In recent years, the failure of many large conventional type breakwater structures has led to a careful examination of the physical processes of wave-structure interaction. Although naturally armouring structures or berm breakwaters, which gain their stability as a consequence of profile readjustment due to wave action, have been around in various forms for hundreds of years, the high incidence of failure of conventional structures has led to their increased use in the past decade.

The interaction of an incident wave with a rubblemound breakwater results in complex flow patterns involving unsteady non-uniform flow. In most cases, it is desirable to construct a breakwater which works in harmony with the flow field; that is to construct a structure with a geometry and armour stone weight gradation which results in natural profile readjustment and subsequent minimization of the applied hydrodynamic loadings.

A naturally armouring or berm breakwater can be described as a mound of rock,often comprised of a wide range of stone sizes, which undergoes reshaping as a result of wave-structure interaction. A consequence of this wave action, a stable profile is developed. Two major processes occur in the development of the stable profile. First, the overall geometry of the structure responds to the nature of the hydrodynamic loadings. Material is sorted and

redistributed into a profile which acts to minimise the applied forces by altering the flow field kinematics. Secondly, this natural sorting leads to consolidation (densification) of the armour layer as stones that move eventually find voids into which they nest.

This type of structure has been used extensively in the past decade and it has been found that in many instances these structures are significantly less expensive than more conventional breakwaters designed in accordance with guidelines given in design manuals such as the US Army Corps of Engineers Shore Protection Manual. The armour stones required are much smaller than those required by conventional stability formulae and a much wider gradation can be used. This allows for the design to be based on the actual quarry output rather than some pre-conceived specification for stone for which a quarry must be found. Experimental studies have indicated that the reshaped breakwater profile can be closely predicted for the design wave conditions and the available material properties. This profile can be used as an initial design. Currently model studies are used to optimize the design and minimise the cost.

The concept of a naturally armouring (or berm) breakwater, on which the applied forces are minimised, has been further supported from the results of a review of breakwaters constructed during the 19th century, breakwater failures and prototype experience with natural profile breakwaters gained in the past decade. A detailed review is provided in report # 1.

The final stable profile developed as a result of wave action will be influenced by a number of variables including the gradation of stones used in the armour layer, the shape of the stones and the angle of wave approach. When a wide gradation of armour stones is used, a natural sorting of stones occurs. In addition, interlocking between stones is developed since stones of a given size tend to roll about the surface until they find voids into which they nest. This allows maximum interlocking between stones to be achieved.

The shape of the stone influences its rolling resistance, its frictional resistance and also influences the magnitude of the applied hydrodynamic forces. Both the stone gradation and the stone shape affect the porosity and permeability of the structure. This has been shown to affect the stability of the structure, by modifying the external and internal flow field kinematics.

The structure also tends to reach its equilibrium profile at different rates for differing wave conditions. Therefore simulation of possible wave conditions during the passing of the design storm is desirable in model tests.

The angle of wave approach affects the magnitude of the applied hydrodynamic forces and therefore influences the relative distance moved by each particle in the direction of the applied force. For very lightweight material, the path of a particle is affected such that motions perpendicular to the longitudinal axis of the breakwater may be decreased while motions in the direction of the longitudinal axis are increased. This may be significant at the head of the breakwater where longitudinal motion may result in excessive reshaping, subsequent instability and constriction of navigation channels.

These mass armoured type of structures develop their stability due to an increase in the total volume of voids of the armour layer (compared with conventional structures) and due to natural

sorting of stones which results in profile adjustment and the development of an armoured profile.

The high total volume of voids of the berm provides a suitable medium through which the incoming wave energy can be dissipated. In a conventional breakwater, the flow is channelled up through the armour stone layer, which is usually only two units thick, and consequently the individual drag force acting on each stone is very high due to a relatively high velocity field in the armour layer. With the berm concept, the incoming wave can spread its energy over a larger mass and area, thereby reducing the velocity field which results in a reduction in the forces acting on individual stones. Because the forces are smaller, smaller sized armour stones can be used. The stability of the armour layer is a function of the stone gradation selected and the thickness of the armour layer over the core. As the stone sizes decrease to the point where individual stones are hydraulically unstable, the breakwater derives its stability through movement of the stones and consolidation of the structure. The profile of the structure is adjusted so that the applied hydrodynamic forces are reduced. The movement of stones also results in a sorting and nesting of the armour stones. As a result, the interlocking between individual stones is maximised.

The natural sorting, or armouring involves a significant amount of motion of stones in the surface layers of armour. It is important to recognise that the motion observed and the reshaping of the profile do not constitute a failure. On the contrary, these processes create a surface layer of armour stones which is more resistant to wave attack than loosely placed stones that are many times the weight of the stones used in this concept. The overall stability of the structure is improved once the nesting of stones has occurred. This motion, however, brings into question the durability of stones. This is discussed later in the report.

The performance of a mass armoured breakwater when exposed to wave conditions exceeding the design conditions is significantly better than the performance of conventional designs under similar circumstances. A conventional design will lose its armour protection relatively quickly when design conditions are exceeded and this may lead to breaching of the breakwater. Damage to the mass armoured design takes place at a much slower rate because the incident wave energy is dissipated over the armour layer and the energy available to remove material from the upper section of the structure is considerably reduced.

This type of structure has been used extensively over the last two decades in Australia, Brazil, Canada, Iceland and U.S.A. In most cases, cost savings of 60 to 70 percent of the cost of a conventional multilayer design were achieved. The concept has the advantage of utilizing the total yield of the locally available quarry. The available material is usually determined before the structure is designed (using trial blasting and geotechnical investigation). The structure is then optimized for the given design conditions (wave height, wave period and water depth). The geometry of the structure is determined to minimise placed quantities. Material is not simply placed in a mound at the natural angle of repose.

The concept of a berm breakwater can also be used in many instances to replace other types of breakwaters currently being used, such as cribwork, steel sheet pile cells and floating breakwaters. Depending on local conditions (design environment and material availability) berm breakwaters may provide the most economical solution.

2.2 ADVANTAGES OF BERM BREAKWATERS

The traditional design of a conventional breakwater (multilayered section illustrated in Figure 2.1) is described in many texts. However, it must be realized that a conventional design may suffer from a number of shortcomings which may create difficulties in the implementation of these structures including (Baird and Hall, 1984):

- Large armour stones are required. At many locations the wave climate dictates (through the design formula) large stones that may be very expensive to obtain or are not available.

  In the latter case the designer must specify concrete armour units which will significantly increase the cost of the project.

- Wastage at the Quarry. The volume of armour and filter stones of the specified weights used may represent only a small percentage of the volume that must be quarried to obtain these stones. This problem is illustrated in Figure 2.1, which shows the yield of a typical quarry and the range of stone weights that can and cannot be used for a breakwater. This breakwater is designed for a significant wave height of 5 m and has a front slope of 2 horizontal to 1 vertical.

  The relative proportions of material required to build this breakwater in 12 m of water are compared to the relative proportions of the usable volumes of the quarry yield in Table 2.1. In this example, over production of armour stones will be required to produce the required volume of core material, although quite often the converse is true.

- Costly Quarry Operations. The quarry operation must be geared to produce armour stones, filter stones and core material. This may require differing blasting procedures. All other material that results from the quarried operations must be sorted and placed in a waste pile.

- Difficult to Construct. Placing continuous layers of armour and filter stones to specified tolerances for location and slope below water requires very careful supervision and inspection, which may be restricted by poor visibility. This may be very problematic in deeper water and/or at location where there is little calm weather. Construction problems may also be associated with requirements to place core, filter and armour material in close succession to avoid damage to a partly built breakwater by wave action. The supply of materials along the breakwater can cause major logistical problems.

- Speed of Construction. The rate of placement of armour stones on a traditional breakwater is limited by careful crane operations, which are relatively slow.

The conventional design procedure based on the Hudson formula provides very little flexibility to the designer to overcome these problems and provide what could be a more cost effective design.

However, it is possible to utilize an alternative design approach which will optimize the use of locally available material and result in the preparation of a design that requires relatively simple but effective construction methods.

The objective of the alternative design process is to prepare a least cost and stable breakwater. This is achieved by utilizing the following procedures:

i) Study the properties of locally available stones.

ii) Define the range of sizes of the locally available material, typically the gradation of curve of a quarry.

iii) Use the smaller fraction of the available material for the core of the structure, as illustrated in Figure 2.2.

iv) Use the large fraction of the available material for the armour, as illustrated in Figure 2.2.

v) Determine the shape and dimensions of the armour protection, which typically involves increasing the thickness of the armour layer, so that during design wave conditions, a stable structure is obtained. This activity, at present, is completed using physical hydraulic model studies. As the dimensions of the armour protection are determined, the relative sizes of core material and armour material (items iii and iv) will vary to accommodate changes in the relative percentages of armour stone and core material required.

vi) Finalize the geometry of the cross-section of the armour to allow for simple construction operations.

One design concept that has resulted from this approach contains armour stones placed in the form of a horizontal berm as illustrated in Figure 2.3. It is the horizontal dimension "B" that is to be determined using model studies. This dimension is a function of the armour stone gradation and incident wave height. In Table 2.2, comparison is made between a conventional breakwater and this alternative design when designed for the same wave conditions.

This breakwater concept has the following features.

- The armour stones can be less than one-fifth the weight of the stones required in a conventional design, as illustrated in Table 2.2. However, the important point is that the concept is intended to make use of the available stones and not necessarily the use of smaller stones.

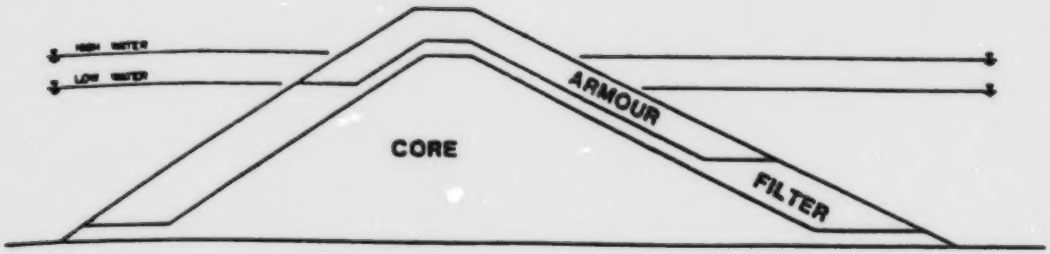
- Maximum use of quarry yield is attained, as illustrated in Figure 2.2.

- Simple Design. Filter layers and toe scour protection berms are usually not required, depending on local geotechnical conditions.

TABLE 2.1

COMPARISON OF RELATIVE PROPORTIONS OF MATERIAL VOLUMES REQUIRED FOR BREAKWATER TO THE USABLE QUARRY YIELD

	Percent of Breakwater Volume	Percent of Usable Quarry Yield
Armour	25	36
Filter	25	26
Core	50	38



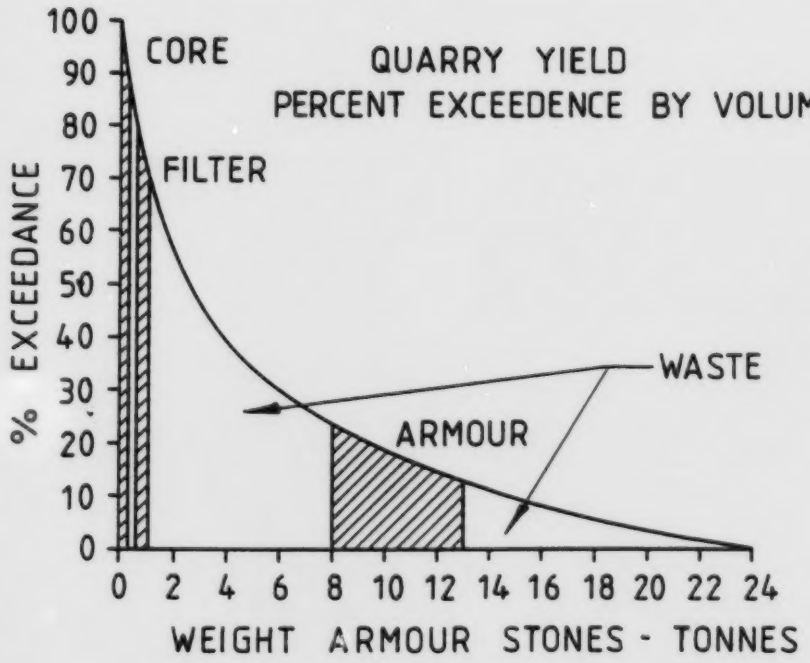


FIGURE 2.1 QUARRY YIELD AND STONE WEIGHTS REQUIRED BY CONVENTIONAL BREAKWATERS

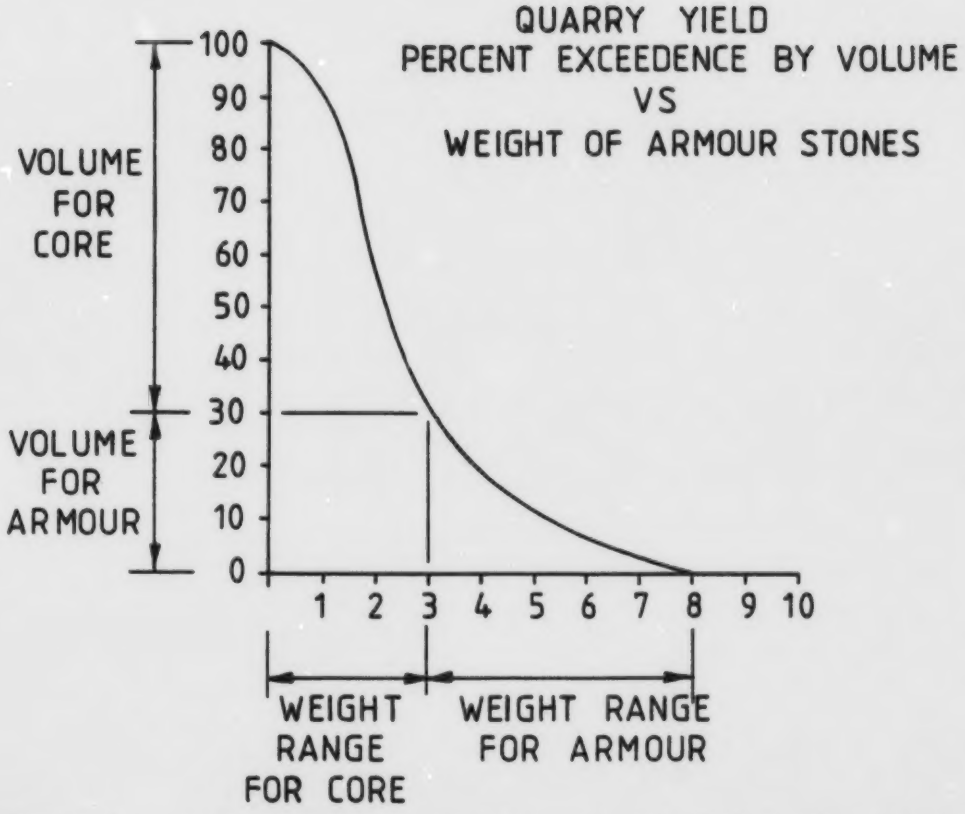


FIGURE 2.2 QUARRY YIELD AND STONE WEIGHTS REQUIRED BY BERM BREAKWATERS

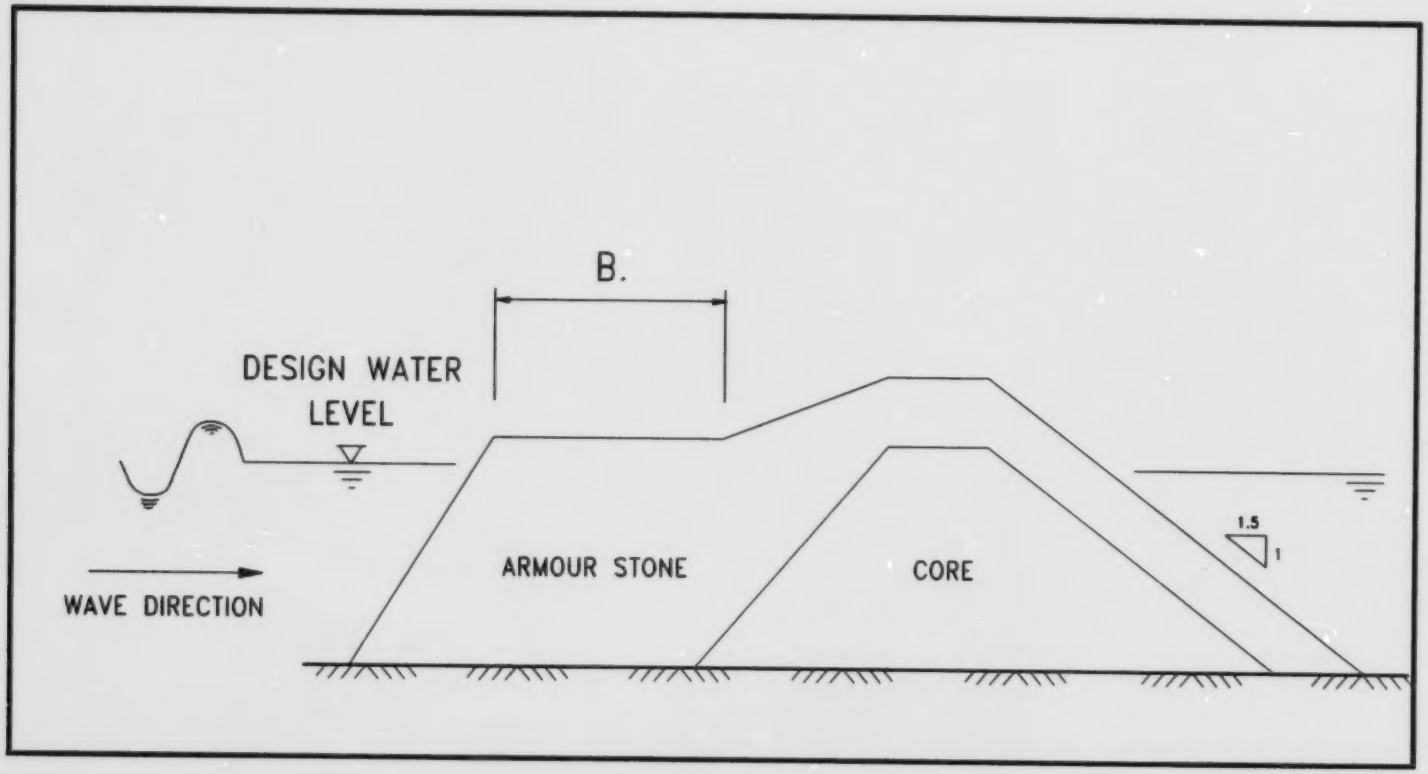


FIGURE 2.3 BASIC BERM BREAKWATER CONCEPT

- The quarry operation consists only of blasting and sorting the stones into two categories (the larger fraction and the smaller fraction).

- The breakwater can be built using land based equipment only (shore connected breakwaters). In most cases a dump and push operation can be utilized and no crane placement is required. Plenty of room is available on the breakwater for construction roads. Moderate wave action during construction is usually of little concern.

- Construction tolerances can be somewhat relaxed and the requirement for extensive underwater inspection can be replaced by relatively simple surveys.

- The performance of the breakwater when subjected to waves exceeding the design condition is significantly better than the performance of a conventional structure exposed to similar conditions. The structure will not fail in a rapid catastrophic manner.

- The total volume of the structure, compared to a conventional structure, depends on the depth of water and the size of stones available. Typically, it may be 10 to 20 per cent greater in depths of 10 to 20 metres. The placement cost per unit volume should, however, be significantly less. For example, transportation costs may represent the most significant cost if a large haul distance is required and thus armour for a berm or conventional design may have the same costs. However, for situations in which transportation costs are not excessive, berm breakwaters may prove economical because of reduced sorting costs of the breakwater materials and reduced construction costs, since individual stone placement is not required.

- The cost of construction of this breakwater in Canada has been found to be significantly less than of the cost of an equivalent traditional structure, local conditions being appropriate.

- Berm breakwaters, because of the nature of their ability to deform and reshape, provide superior stability compared with conventional breakwaters when large water level fluctuations are present. Previous research has shown that the worst case scenario for reshaping occurs at the maximum water level. In tidal regimes, one or more complete tidal cycles will occur during the passage of a storm and, consequently, reshaping may not be as severe as it would be in a scenario in which the water level is fixed over the duration of a storm. In this context, long term variations in water levels, such as those exhibited in the Great Lakes system, may prove to be the most significant with respect to berm breakwater reshaping.

TABLE 2.2

COMPARISON OF STONE SIZES POSSIBLE WITH BERM DESIGN AND CONVENTIONAL DESIGN

Design Significant Wave Height (Metres)	Range of Armour Stone In New Design (Tonnes)	Stone Weight for Conventional Design (Tonnes)	
		Slope	
		1:1.5	1:2
4	0.2 - 1.1	7.1	5.3
6	0.7 - 3.5	24	18
8	1.8 - 8.4	57	43

Note: The size of armour stones used in the proposed concept should be dictated by the yield of the local quarry and may be larger than shown. The above indicates possible lower limits that may be considered

3.0 FACTORS INFLUENCING THE DESIGN OF BERM BREAKWATERS.

The optimum design of a breakwater is a complex process which involves careful assimilation of data dealing with the various aspects of the design and merging this data so that the ultimate result is a design that meets required performance and stability criteria while providing the most economical solution. In order to achieve this goal, the design process involves a number of stages leading to a step-wise progression from data assimilation to conceptualization to preliminary design and further refinement resulting in the final design. Above all,the design must be functional, constructable, maximize use of local materials and meet the necessary design requirements. It is important that the various stages of the design process are interactive.

Each major stage of the design process is discussed below in a general manner.

STAGE 1 - PROJECT DEFINITION

In the first stage of analysis, the requirements of the proposed facility must be well defined. Selection of these requirements will have a direct effect on the type of solution developed and thus on the cost/feasibility of the project. Items which need to be clearly defined include various aspects of the overall project as well as specific aspects associated with the breakwater(s).

Overall project

- purpose
- preferred location
- protection requirement (eg. how many boats, type of boats, shore facilities, etc.)
- acceptable wave agitation, operation limitations
- type of internal walls (reflection versus access), harbour characteristics.
- type of docking system (fixed, floating, removed in winter, etc.)
- determination of realistic project life

Breakwater

- overall layout and berm requirements (function of agitation)
- access, topside facilities
- overtopping allowable or not
- maximum allowable crest elevation (aesthetics)
- can ongoing maintenance be accepted (therefore lower initial costs but with maintenance budget)

It is important that the aspects of both the overall project and the breakwater itself are considered mutually in order to arrive at the most sensible project statement. In essence, this stage does not involve detailed technical study; rather, a good knowledge of exactly what is required at the given site must be developed.

STAGE 2 - ASSIMILATION OF DESIGN INFORMATION

Before concepts can be developed to meet the requirements defined in stage 1, design data relevant to the project must be collected. This includes environmental design data (wave climate,

water levels, bathymetry, currents), indirect design data (geotechnical, ice, seismic), characteristics of locally available materials for use in the project, knowledge of the local construction resource base, and developing an understanding of the environmental impact of the project.

Assimilation of environmental data will include utilization of desk studies, collection of prototype data, examination of historical data, and undertaking specific site investigations. Listed below are the major design parameters required along with common methods of obtaining these.

Wave Climate

Ultimately, a designer would like to have many years of recorded wave data at the site to estimate the design wave height, period and direction. However, this is rarely the case and the designer is faced with developing the design wave data using a combination of methods including wave hindcasting (spectral, parametric, simplistic), comparing the hindcast data with available recorded data (hindcast calibration), transforming the hindcast waves from deep water into depths associated with the job site (spectral saturation, linear wave ray, simplistic geometrical techniques) and finally producing long term statistics by utilizing extreme value analysis (variability in the type of equation, method of fit, type of error analysis). A prescribed level of wave attack (a recurrence interval associated with a certain risk or probability of occurrence) must be specified. Significant error may appear at each of these steps and thus it is imperative that the studies are undertaken using methods with a sound technical backing. Sensitivity analyses should be undertaken at each of these stages. Specific technical details are discussed in "Guidelines - Design of Rubblemound Breakwaters", AES/SAG 1-2:90-10, Public Works Canada, (1990), hereafter referred to a PWC (1990).

Water Levels

In tidal areas, analysis of extreme tides coupled with a knowledge of storm dependent set up (barometric, wind stress and that associated from irregular wave setup must be included) is undertaken in order to determine the maximum and minimum design water elevation. It is important to consider both extremes as either condition can lead to the harshest environmental forces acting on the breakwater (for instance, it may be that at high water level, the design wave is non-breaking, whereas at low water breaking is induced - this would mean that wave runup levels (which dictate the crest elevation) would maximize at high water level, whereas the maximum destabilizing forces acting on the breakwater may occur at low water level).

Some areas, such as the Great Lakes, are subject to long term variations in water level. These can often be more damaging to a breakwater structure. Methods of analysing long term trends in lake levels are not well defined. Conventional methods of extreme value events are technically incorrect because the condition of assuming independent events is not usually met. Specific technical details are discussed in PWC (1990).

Bathymetry

Bathymetric data is required both in the immediate vicinity of the site and extending into deep water (particularly to where the deep water waves were hindcast). Bathymetric data may be obtained from existing field sheets, (Canadian Hydrographic Service), nautical charts, or by undertaking hydrographic surveys of the area. When working in areas susceptible to short term changes in shoreline and/or nearshore bathymetry, it may be wise to up-date existing surveys, particularly if older than a few years. The bathymetric data will be used for calculating shallow water transformations of deep water wave data, and may be utilized should hydraulic modelling be undertaken.

Currents

Currents rarely have an influence on the hydraulic stability of a breakwater; however, they will be an important parameter when analysing the environmental impact of the project. Information on currents will usually have to be collected for each particular site (although limited data for a few sites has been collected by the Marine Environmental Data Service, Department of Fisheries and Oceans).

Assimilation of indirect design data must be undertaken on a site specific basis. Included in this data set are geotechnical conditions, winter ice conditions (type of ice, movement, typical thickness, etc.) and seismic conditions Geotechnical data would be developed based on a site investigation. Ice conditions may be obtained from "Ice Summary Charts", available from ICE FORECAST CENTRAL, Atmospheric Environment Service. Seismic conditions and methods for designing marine structures in these conditions have been developed for Public Works Canada (Seismic Design of Marine Retaining Structures, AES/SAG 1.2:87-5, 1986). It is not the intent of this report to detail these types of studies, only to make the reader aware that these indirect design data will have an influence on the design concept selected and its subsequent final design. For instance, if a structure is required in an area of sensitive soils, it may not be possible to extend the structure to the crest elevation dictated by hydraulic considerations, and thus a compromise low crested structure which is heavily overtopped may be the only solution.

The characteristics of locally available construction material has a direct influence on the conceptualisation and design stages. Therefore, information regarding known and potential sources of rock must be assembled. Known sources include quarries in operation, quarries used previously for breakwater construction and sources of field stone. Potential sources include existing quarries no longer in use and new quarry sites.

The selection of a quarry capable of producing sound, competent rock is based on a number of governing criteria including supply, sizing, rock quality, potential quarry yield and transportation

distance. Guidelines for source selection and procurement of armour stone have been presented in "Guidelines for Source Selection and Procurement of Armour Stone for Coastal Projects", Golders Ltd. report for Public Works Canada, (1989), in considerable detail and the reader is referred to this document for specific details. Golders make several recommendations regarding the type of study required to determine the yield of the quarry and the associated material properties. These investigations should include determination of characteristics of armour, filter and core size materials.

For large projects in areas where no known quarries are operating, it is usually cost effective to undertake material searches to identify sources of construction materials. Smaller projects with low construction budgets cannot normally support the costs of a comprehensive materials investigation; frequently, these projects go to tender with only a cursory knowledge of available materials. This scenario may often lead to unsuccessful projects. Golders (1989) indicate that although an investigation of materials must be tailored to the budget and scale of the project, a basic investigation for any scale project must address four points:

- define the economic transportation distance
- locate quarry sites for providing the required stone within that distance
- assess the macro and micro- characteristics of the rock in relation to predefined specifications
- determine the yield of the quarry in terms of the different sizes of stones

Guidelines for completing these tasks are given for various size projects. The site investigation consists of a number of phases including desk studies, site inspection, site investigation, laboratory testing, trial blasting, and competence testing of quarried rocks. Details of the methods of each of these phases are provided in Golders (1989).

A data base can be built up which will identify potential resource locations for breakwater materials within each region. The database should include quarries which have been used previously for breakwater materials (including a description of the performance of the material in service on the breakwater), quarries in operation (usually producing aggregates), quarries which have been in operation at some time but are currently shut-down, and potential quarry sites.

Table 3.1 gives an example of a quarry summary sheet which should be completed for all potential sources of materials. Table 3.2 provides a sample of a breakwater summary sheet, which should be completed for each breakwater project undertaken by PWC

The durability of stone for use in breakwater projects is a topic which has recently seen a surge of research activity. Many existing prototype breakwaters are exhibiting damage associated with deterioration of the material used to construct the breakwater. In order to assess the durability of stone for use in breakwater Fookes and Poole, 1981, suggest the tests indicated in Table 3.3

TABLE 3.1 EXAMPLE QUARRY DATA SHEET (from Golders, 1989)

QUARRY DATA SHEET

NAME _____ CODE NO. _____

LOCATION _____ PROVINCE _____

GRID COORDINATES (NTS) NORTH _____ EAST _____

MAP SHEET _____

OWNER _____

ADDRESS _____

_____

PROVINCE _____ POSTAL CODE _____ TELEPHONE # _____

ROCK TYPE)S) _____ _____ _____

RESERVES _____ _____ _____

YIELD _____ _____ _____

ROCK PROPERTIES AND COSTS

ROCK TYPE	$MgSO_4$%	BULK DENSITY	L.A.LOSS	MAXIMUM SIZE	COST/ TONNE	DATE
A.						
B.						
C.						
D.						

ROAD ACCESS (WEIGHT RESTRICTIONS)

_____

AGGREGATES (NOTES)

_____

COMMENTS

_____

_____

COMPILED BY _____ DATE _____ REVISION DATE _____

TABLE 3.2 EXAMPLE BREAKWATER DATA SHEET

BREAKWATER DATA SHEET

NAME _____ CODE NO. _____

LOCATION _____ PROVINCE _____

GRID COORDINATES (NTS) NORTH _____ EAST _____

MAP SHEET _____

WATER BODY _____

	DATE	ROCK TYPE	SIZE 1	SIZE 2	SIZE 3	SOURCE CODE NO.	COST 1	COST 2	COST 3
BUILT									
REPAIRED 1									
REPAIRED 2									
REPAIRED 3									
REPAIRED 4									

PROJECT DESCRIPTION

_____

_____

_____

_____

COMMENTS/UPDATES	MADE BY	DATE

aimed at assessing the following properties of armour stone:

- hardness
- resistance to mechanical abrasion
- toughness (impact resistance)
- resistance to weathering

However, these tests, on the whole are designed to investigate the usefulness of material as an aggregate source. In addition to specifying the actual tests, specifics such as methods of obtaining test specimens, what size they should be, how many specimens should be assessed and how often samples should be taken, need addressing. Currently, the engineering community is trying to address this area of study, as results become available they need to be incorporated into the design process.

However, based on existing knowledge, specification for addressing rock quality have been included in Appendix B and are based on current Public Works Canada practice.

Additionally, during this stage of the design process consideration must be given to the method of construction which will be utilized. This will be very dependent on the area in which the project is being completed, as the availability of various types of both land-based and marine construction plant vary from region to region.

It would be wise to assemble a data base similar in concept to the data base discussed for breakwater materials. This could be completed on a regional basis by providing an equipment summary sheet to contractors expressing an interest in constructing breakwaters. Such a data base would be relatively easy to develop as most contractors would be willing to provide a summary of their capabilities. With such a data base, the design of the breakwater could be advanced to incorporate limitations of locally available equipment. For very large scale projects, this may not be a major concern since contractors bidding for these projects can easily obtain equipment necessary for most practical breakwater designs.

TABLE 3.3

FOOKES AND POOLE, 1981

Rock Property	Rock Material Tests	Simulated Performance Tests
Hardness (The resistance to abrasion)	Aggregate abrasion test (BS 812)+ Aggregate attrition test (BS 812) Aggregate impact test (BS 812)* Aggregate crushing test (BS 812)* Polished stone value (BS 812)+ Scratch hardness (ASTM C-235)* Specific gravity (BS 812)**	Aggregate abrasion test (BS 812)+ Los Angeles abrasion (ASTM C-535)*
Toughness (The resistance to fracture under impact)	Aggregate impact test (BS 812)* Aggregate crushing test (BS 812)* Unconfined compressive strength (seawater and fresh water wet and dry (BS 812)** Franklin point load test (Broch and Franklin 1972)** Schmidt rebound number (Duncan 1969)*	Drop off back of a truck* Tests as for rock material but after weathering tests*
Soundness (The resistance to weathering i.e. the durability)	Petrographic examination (cf ASTM C-295)** Clay mineral analysis (X-ray, DTA, Methylene blue, etc) Water absorption and apparent, saturated surface dry and over dry specific gravities (BS 812 and others)**	Weathering soundness (ASTM C-88)** Wetting and drying cycles (salt water and fresh water)

BS indicates British Standards.
ASTM indicates American Society for Testing Materials.
** Potentially the most appropriate tests for breakwater stone.
* Potentially helpful tests.
+ May be misleading.

STAGE 3 CONCEPTUALIZATION

Once the project requirements have been defined and the data relevant to the project have been collected, the process of conceptualization can be undertaken. This will involve developing structures and their layouts to meet as many of the project requirements as possible, while maintaining an economical balance by taking into consideration limitations of material sources, available construction methods and other indirect data such as geotechnical, ice and environmental considerations.

For instance, if local quarries are found to produce massive blocks of armour stone, it may be prudent to proceed with a conventional two stone thick armour layer design. Relatively steep slopes could be utilized if sufficient size stones are available. If on the other hand, local quarry output consists of relatively small stones (relative to that required for hydraulic stability using a conventional design), it would be wise to proceed with an alternative design which might consist of a berm breakwater or of some type of composite berm/conventional breakwater. There are a large number of combinations of structure types; the key element in providing an economical design is to utilize local resources (materials and equipment).

STAGE 4 PRELIMINARY DESIGN

The concepts developed in stage 3 are put through a preliminary design process. Although this is called preliminary design, for small projects, this stage may in fact be the final design stage (as the project budget would probably not support physical modelling and advanced technical methods). This stage of the design process involves undertaking desk studies using various empirical and analytical techniques developed for breakwater design. This would include calculations to:

* estimate the required mass of each of the types of breakwater materials (armour, core and filter (if required))

* decide on the overall geometry of the structure (slopes, crest width, crest elevation, layer thickness, etc.)

* determine wave runup and overtopping levels (if allowable)

* determine agitation levels in the marina or harbour basin

It must be recognized that the empirical and analytical techniques developed for breakwater analysis are often based on simplistic techniques which require many assumptions (which are often not valid in prototype) in order to advance a solution. As a consequence, these methods often have limited reliability. For this reason, these methods are included under the title of preliminary design techniques. Optimization of the design leading to a final stable design can only be accomplished with a high level of confidence if properly designed physical hydraulic model studies are undertaken. These model studies themselves are subject to scale effects which may influence the results obtained. However, it is possible to evaluate these effects and have confidence in the modelling results. This is discussed further in PWC (1990).

It must also be recognized that small scale projects may not have the budget available to undertake the necessary steps involved in producing a final design. Consequently, the preliminary design developed is often the final design. In this case, the designer must be careful to utilize the best available methods, understand their limitations and to incorporate a sufficient factor of safety into the design to ensure its successful completion and service.

STAGE 5 FINAL DESIGN

For large scale projects and for those small scale projects with sufficient budget, the preliminary design(s) prepared during stage 4 must be optimized and assessed using a physical hydraulic model study. Modelling will allow any shortcomings of the design to be identified and will enable the design to be optimized with respect to locally available materials and construction methods. In almost all instances, hydraulic model studies are cost-effective, in that the cost of undertaking the studies will be offset by savings in the cost of the structure.

Many aspects of the final design can be assessed in the model including:

- hydraulic stability (of front and backslopes and of crest)
- overtopping and runup levels
- wave agitation levels in the marina
- functional performance criteria

Sensitivity analyses are easy to undertake once the model is operational (for instance, the influence of breakwater slope on armour stability or the influence of breakwater configuration on wave agitation levels).

However, hydraulic models are not without their limitations and it is important for the designer to recognize exactly what these limitations are. Primarily a result of scale and model construction, these effects may be either conservative or non-conservative. Minimization of these effects can be achieved by careful scale selection and proper construction (model) techniques.

STAGE 6 PRODUCTION OF PLANS AND SPECIFICATIONS

The final stage of the breakwater design process is the production of working drawings and construction specifications. These must accurately represent the design as developed during the previous five stages with careful consideration given to material specifications, placement tolerances and contamination of the various layers of material. These specifications should include:

Material Specifications

- gradation curves for the various materials
- specified rock properties (ie specifically the tests that must be undertaken and what prescribed values need to be achieved)
- frequency of testing
- methods of dealing with contaminated material or material not meeting spec (for before placement scenario and after placement)
- methods of visual inspection

Placement Tolerance

- vertical and horizontal placement tolerances
- allowable overlap of the various layers during construction
- alignment tolerance
- methods of surveying the structure
- methods of approving completed sections
- remedial measures for repairing damage resulting from storm waves attacking an uncompleted structure

4.0 DESIGN GUIDELINES

At present, the design of a berm breakwater must be determined solely from the results of hydraulic model studies. A number of trial and error solutions must be assessed before the final design is narrowed in on, often resulting in a lengthy, costly model programme. Additionally, each breakwater at each site will probably be constructed with a different gradation of armour stone (it should be since the idea of the concept is to maximize use of locally available material and most quarries have varying characteristics). This results in the requirement of "hand" picking the modelling stones to match the estimated prototype gradation (again a costly procedure). If during construction, it is found that the actual prototype gradation varies significantly from the estimated gradation used in the hydraulic model studies, additional tests are required to properly assess the influence of this change on the final design.

Guidelines presented in this report are intended to eliminate most of the initial trial and error tests and to provide a basis for assessing the influences of changes in breakwater material specifications on breakwater stability, which may arise following initiation of construction. Development of these guidelines was achieved by undertaking an extensive series of hydraulic model studies in which stone gradation, stone shape, wave climate, angle of wave attack and design storm profile was varied over a wide range which should encompass most possible design scenarios. Data measured in these tests was analyzed (and described in report 1) and subsequently design guidelines were prepared.

These guidelines can be used in the following manner:

(1) For a new breakwater site, the characteristics of the locally available quarry should be estimated (trial blasting or geotechnical investigation). For the wave conditions which occur at the site, a preliminary design can be selected from the guidelines.

(2) The preliminary design can be adjusted along the length of the structure to take into account variations in depth and/or wave conditions (will assist in minimizing the cost of the structure).

(3) The preliminary design developed in (1) and (2) can be tested using a hydraulic model. By using steps (1) and (2) a considerable modelling effort has been saved.

(5) If during construction, it is found that the preliminary estimate of the quarry yield was not realistic, modification to the final design can be made based on information presented in the guideline, eliminating the need for re-initiating the modelling program.

(6) Cost estimates can be prepared for any breakwater site based on a preliminary design of the structure using the guidelines. These cost estimates should be very realistic since major alterations to the preliminary design should not be required.

4.1 DETAILS OF THE STRUCTURE

As discussed in chapter 2, there are many variations of an alternative design, which can be developed based on functional performance requirements, locally available materials and construction methodologies and other restrictive requirements. Wherever possible these factors must be incorporated into the design.

One very successful alternative breakwater is the concept of berm breakwater as discussed in section 2. The design guidelines in this chapter are for a specific initial geometry of berm, which has been developed based on considerable amount of prototype and modelling experience and also takes into account the practical aspects of construction.

The basic shape of the cross section is shown in Figure 4.1. The basic components of the design are as follows:

1. The berm, indicated by a width B, is typically placed 0.5 to 1 metre above design high water level. This is to facilitate construction during periods of high water. (This elevation may be set higher than recommended provided the berm width, B, is maintained. In this case, no compromise in stability is made.

2. The front slope of the armour stones is the natural angle of repose of the material. This should be in the range of 1:1.15 to 1:1.3 depending on the shape, size and grading of armour stones. It is suggested that a value of 1:1.25 be used for volume and cost calculations.

3. Immediately behind the berm is an upper slope of 1:3. This value is recommended as it facilitates easy construction and helps in reducing wave runup levels (thus allowing either less overtopping or reduced crest elevations). Should steeper upper slopes be used, it is recommended that hydraulic model studies be undertaken to verify the hydraulic performance of the structure (upper slope stability and overtopping performance).

4. The core front slope is indicated at the natural angle of repose. However, slopes as flat at 1:2 are acceptable (this will increase core volume and decrease armour volume) if a better balance in quarry use is desired. Additionally, reshaping of the unprotected core may occur during construction. As long as it is within the bounds of a 1:2 slope, reconstruction is not required.

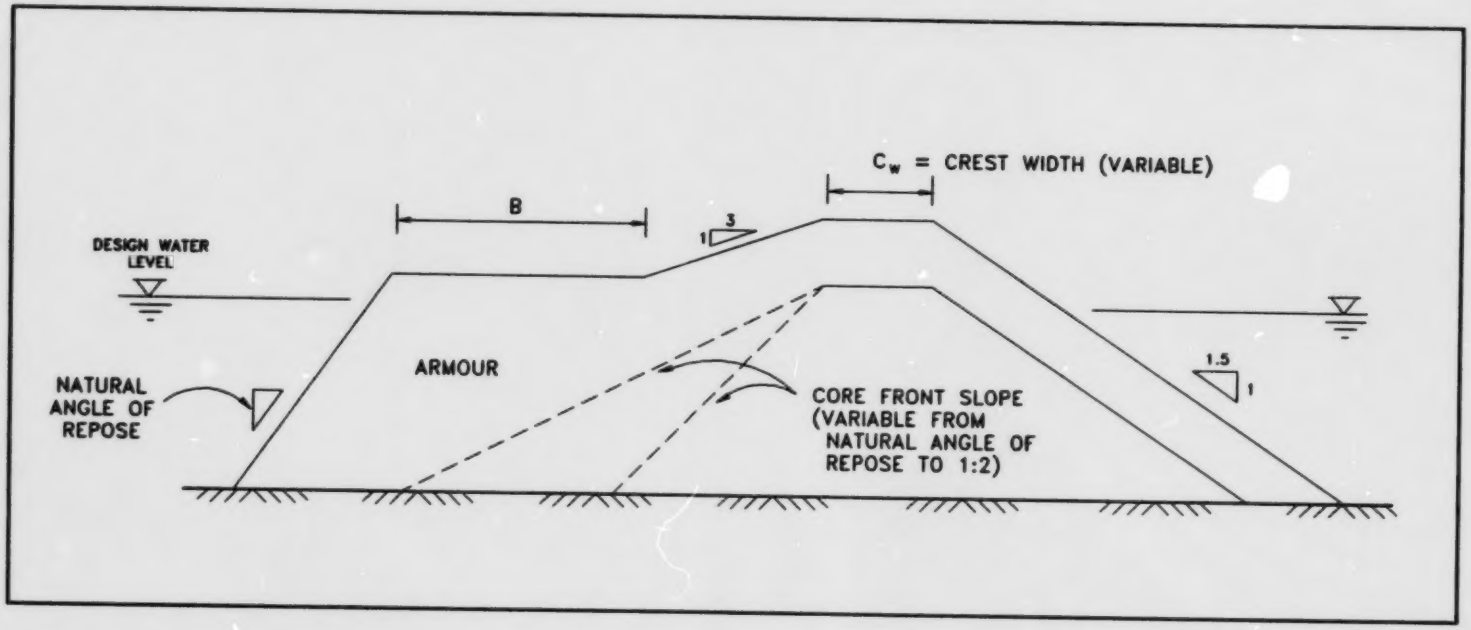


FIGURE 4.1 BERM BREAKWATER CROSS SECTION

The elevation of the crest of the core is selected to coincide with the elevation of the top of the armour stone berm. This aids in simplifying construction, allowing quick bulk placement operations.

5. The crest elevation has been selected so that no overtopping of the structure will occur during the design event. This is desirable for two reasons; first, no overtopping allows for facilities (lights, pipelines, etc.) to be constructed on the crest and second, no overtopping means that the design of the backslope of the breakwater can be maintained at a minimum level of protection. Should overtopping of the breakwater be allowed (or desirable) then hydraulic model studies must be completed in order to obtain a final design. Stability of the backslope, agitation within the harbour and overall performance of the breakwater should be assessed during these studies.

6. The slope of the backslope of the breakwater should be constructed at 1:1.5. This allows for minimum protection to be placed on the structure (a thickness of armour equivalent to two times the D_{50} value of the armour stones). Should the crest be overtopped, the comments addressed in (5) above must be reviewed.

4.2 CALCULATION OF THE DESIGN CROSS SECTION

STEP 1

Based on a review of quarry information determine the characteristics of the armour gradation.

D_{50} = _____ $\frac{D_{85}}{D_{15}}$ = _____

where D_{50} = diameter that 50% of the material is finer than

D_{15} = diameter that 15% of the material is finer than

D_{85} = diameter that 85% of the material is finer than.

Figure 4.2 shows an example of a projected armour gradation with values of D_{50}, D_{85} and D_{15} indicated. The ratio of D_{85}/D_{15}, often called the uniformity coefficient, describes the relative grading of the material. An initial estimate of the armour grading can be obtained from the actual quarry output assuming a lower limit of 500 kg and utilizing all material above this limit as armour. All material below this limit would be core. Following completion of step 4, this lower limit of armour size can be adjusted to reflect the actual ratio of core/armour volume based on the geometry developed in step 4 and adjusting the lower limit so that 100% utilization of the total quarry output is achieved. For example, if based on the geometry developed in step 4, the core volume represented 40% of the total volume of the structure, the lower limit of the armour would be set at the D_{40} value on the total quarry yield curve and the armour would consist of the largest 60% of the quarry yield. New values of D_{50} and D_{85}/D_{15} relative to this fraction of material would be required. This may require several iterations of steps 1 to 4; modifying D_{50} and D_{85}/D_{15} as required.

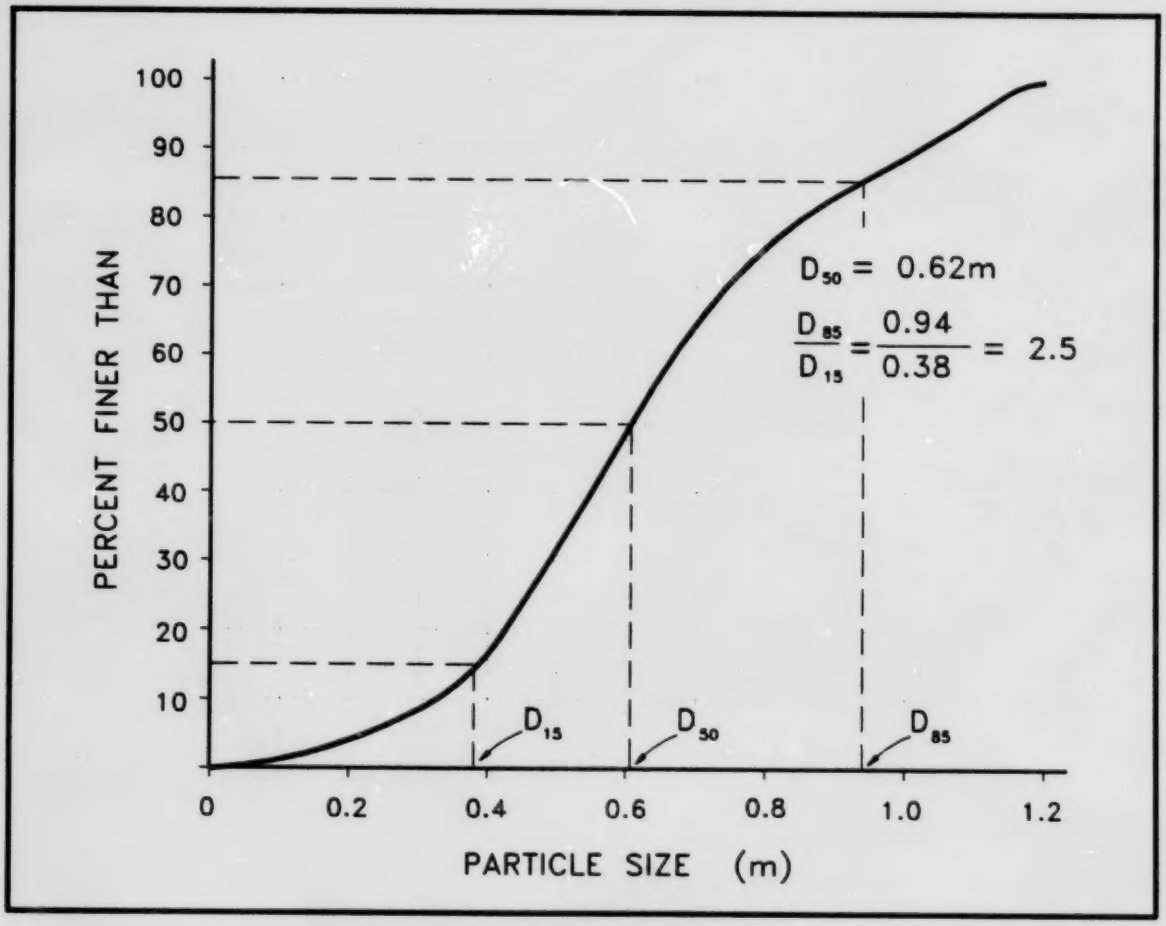


FIGURE 4.2 EXAMPLE GRADING CURVE

STEP 2

Estimate the fraction of rounded stones likely to be in the gradation (P_r)
(note P_r is a decimal fraction not percentage)

P_r = _____

This may account for the inclusion of rounded stones in the original gradation (particularly in the case of field stones) or for rounding which may be expected to occur during the reshaping. A value of $P_r > 0.5$ (50%) is not recommended. Armour stones which will develop more than 50% rounding may not have sufficient strength and durability characteristics for use in a breakwater environment. Test methods for assessing the strength and durability of the armour material are discussed in Appendix B. In most typical applications, it is the smaller stones which will move around the most and thus be the most susceptible to rounding. The larger stones do not tend to move as readily and are thus more inclined to retain much of their original shape.

Determining the value of P_r will usually be a qualitative estimate and thus it may be prudent to undertake a sensitivity analysis by using several values of P_r and determining the appropriate cross sections.

STEP 3

Based on the estimates of P_r, D_{85}/D_{15} and D_{50}, select the appropriate chart in Appendix A. These charts (an example shown in Figure 4.3) provides an estimate of the berm width (B) required as a function of the design significant wave height, H_s. Suppose the design wave height for a particular location was H_s = 4.0 m, from figure 4.3, it can be seen that B is a function of D_{85}/D_{15}. Selecting D_{85}/D_{15} = 3 (typical for many quarries) then the berm width required is B = 7.5 m.

If it was desired to evaluate the effect of the percent of rounded stones, then figures of B versus H_s for other values of P_r (other than P_r = 0 used in Figure 4.3) could be selected. It turns out if P_r = 0.5 (maximum recommended) then for H_s = 4.0 m, D_{50} = 1 m, D_{85}/D_{15} = 3 the required value of B is 10 metres. If there was uncertainty over the value of P_r, then the largest value of B should be selected.

STEP 4

Once the value of B has been determined, the overall geometry of the final structure can be determined using figure 4.4. The factor, SF and the multipliers for terms a, b and C_w arise from consideration of scaling the model study results to prototype conditions.

STEP 5

Volume and cost estimates using normal methods can then be undertaken for the design cross section determined in Step 4.

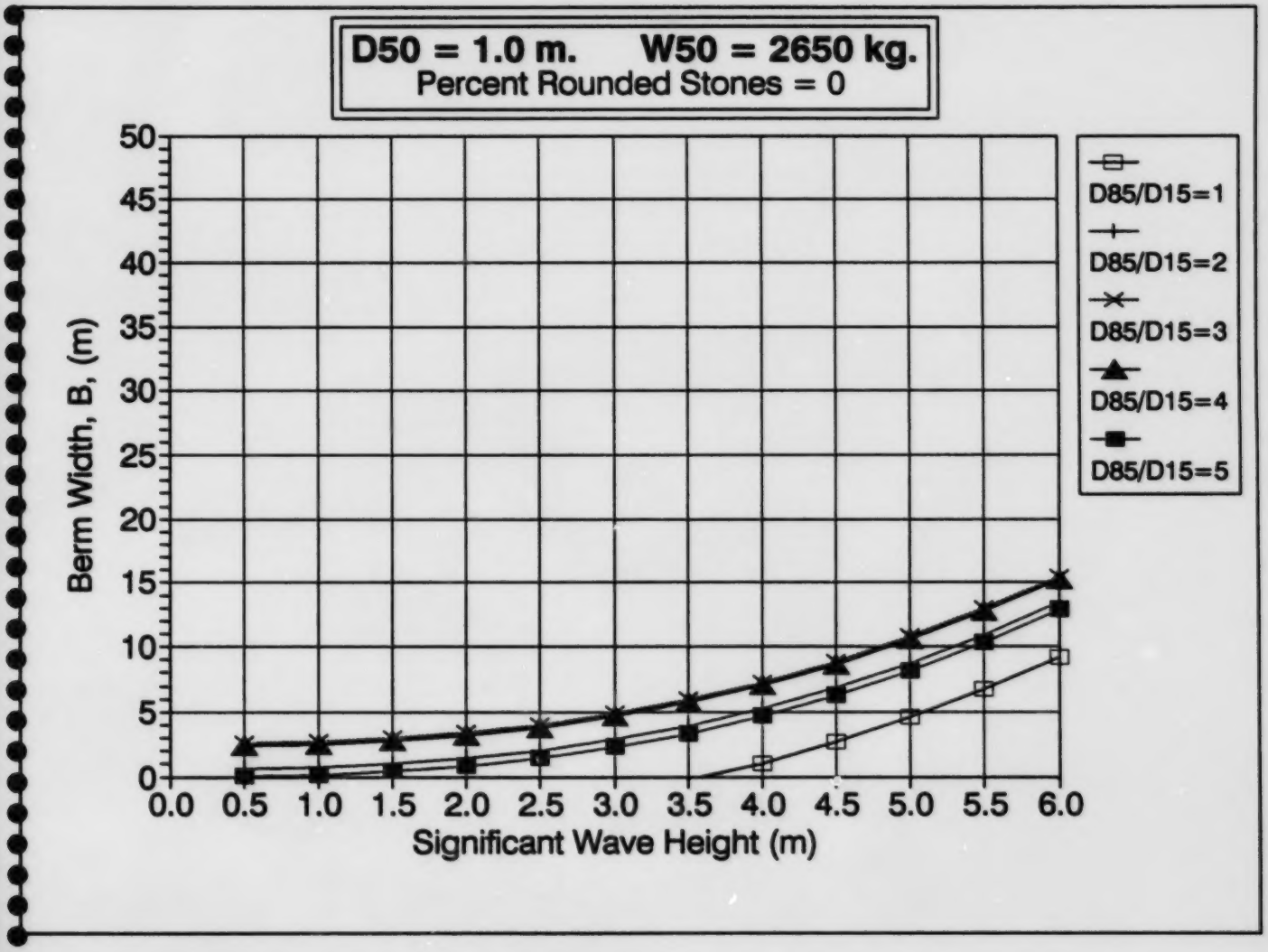


FIGURE 4.3 EXAMPLE DESIGN CHART

LEGEND

$SF = \frac{H_s}{.12}$ where H_s = Design Significant Wave Height

B = Berm width from Appendix A (metres)

d = Water depth (at high water) (metres)
a = SF x 0.025 (metres)
b = SF x 0.15 (metres)
D = b x 3 (metres)
C_w = SF x 0.15 (metres)
E = (a + b + d) x 1.5 (metres)

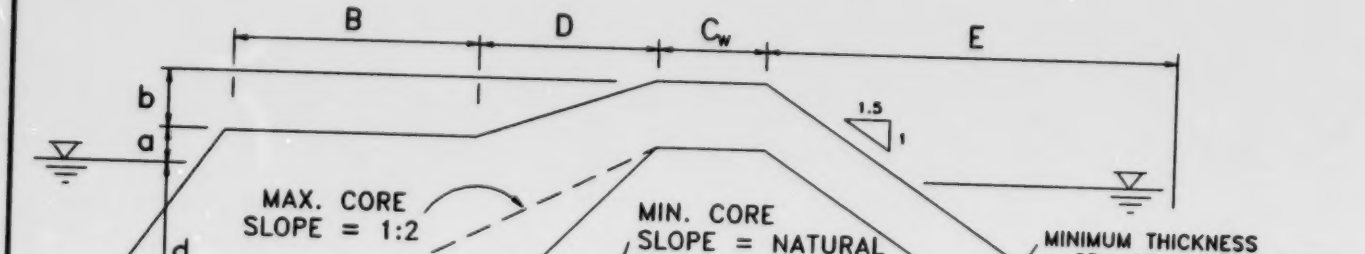


FIGURE 4.4 FINAL DESIGN GEOMETRY

STEP 6

The procedures outlined in steps 1-5 can be repeated to assess the sensitivity to variations in any of the design parameters (H_s, D_{50}, D_{85}/D_{15} and P_r). The conservative design should, in most circumstances be selected. Limitations associated with the designs produced using these guidelines are discussed in the next chapter.

5.0 LIMITATIONS

As with any design procedure based on empirical relationships developed using a set of hydraulic model studies, certain limitations will apply. The hydraulic model studies undertaken to develop the design guidelines in this report, although very extensive and covering a wide variation in design conditions, simply cannot encompass every possible design scenario that may be encountered.

There are a number of circumstances that the designer may encounter which will require additional design work to be undertaken. The design prepared using these guidelines can provide the initial estimate of the size of structure required (this will result in a considerable savings in cost and effort when developing the final design). In most cases the additional design work will consist of undertaking detailed hydraulic three dimensional model tests. These tests should be conducted in accordance to the well known laws of dynamic similarity and must only be completed by qualified personnel. Guidelines for undertaking these studies have been presented in Public Works Canada AES 1-2: 90-10.

5.1 SPECIFIC CASES - LIMITATIONS

5.1.1 **Large Projects**

For large projects in which the placed volumes exceed 100,000 cubic metres or total cost exceeds $1.5 M, the final design of the breakwater should be completed using a hydraulic model study (the initial design and cost estimate can be completed using the guidelines). In almost all cases, the cost of the hydraulic model study will be recovered due to savings achieved in the final design phase(s). It should be noted that within a practical limit, the cost for model tests are relatively fixed and are not project dependent. Obviously for larger areas to be modelled, model construction costs will increase; but generally modelling costs do not vary significantly from project to project.

5.1.2 **Complex Bathymetry**

The model studies used as a basis for the design guidelines were undertaken with simplistic planar bathymetry; thus the design wave height was uniform over the bulk of the structure. In cases where the bathymetry is complex (very irregular, sink holes, mounds and large degrees of curvature in the contour lines) localized shallow water wave transformations can occur which can substantially alter the magnitude and direction of the waves on the breakwater. As a result, localized maxima, which may be up to 50 - 100% higher than the design wave can occur. Obviously the stability of the structure in the area of these localized maxima will be significantly altered.

The only correct way in which the localized modifications to wave climate can be determined is to carefully model the bathymetry of the seabed in the vicinity of the structure, and design the structure based on observations made in the hydraulic model tests. Numerical methods do not have the ability to model these localized maxima with sufficient accuracy.

5.1.3 Modifications to the Basic Geometry

In certain circumstances, it may be desirable, as a result of aesthetic, logistical or economic reasons, to modify the geometry of the structure designed in accordance to the guidelines. For example, in many locations it is desirable to provide a relatively low crested structure so as to not obscure the view of the water from within the harbour/marina bounds. This will result in a structure which may be heavily overtopped and consequently redesign of the crest and backslope will be required. Additional changes which fit into this category include reduction in the crest width, change in slope of the backslope, change in slope of the upper 1:3 slope and modification of the berm height.

In all these cases, the final design should be assessed using a properly designed hydraulic model study.

5.1.4 Marina/Harbour Layout

Obviously the information presented in these guidelines deals with the design of the breakwater only. In some circumstances, the overall layout of the basin (breakwater alignment, breakwater shape and entrance configuration) needs to be considered in order to provide satisfactory performance criteria within the basin. The most reliable method of achieving this is to undertake a hydraulic model study. If a study is undertaken then it would be prudent to undertake stability tests in conjunction with the wave agitation/layout tests. Careful selection of the appropriate hydraulic model scales will allow for both breakwater stability and basin performance to be assessed simultaneously. It is suggested that wherever detailed studies are required to determine the layout of the basin, detailed breakwater stability studies also be carried out.

5.1.5 Water Level Fluctuations

If a significant tidal range or long-term variation in water level occurs at the site, hydraulic model investigations should be undertaken to evaluate the influence of the water level fluctuation on the stability and overall performance of the breakwater.

5.1.6 Head Stability

It may be desirable to minimize the amount of reshaping occurring at the head of the breakwater, where migration of material as a result of reshaping may not be desirable. For instance, if agitation conditions are such that a very narrow entrance is required, a quasi-static head may be required. This can be achieved using a number of solutions such as increasing the elevation of the berm, increasing berm width or increasing armour size. In all cases, these modifications must be undertaken using three dimensional hydraulic model studies.

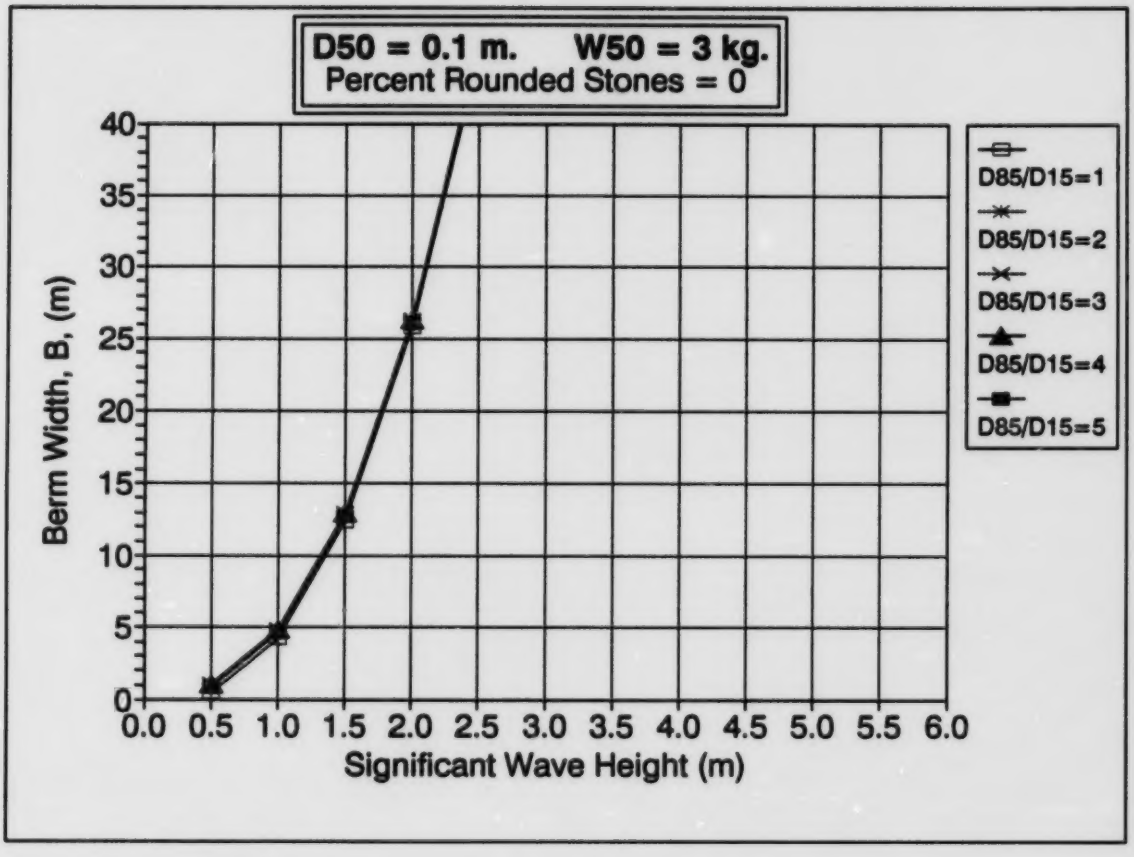
REFERENCES

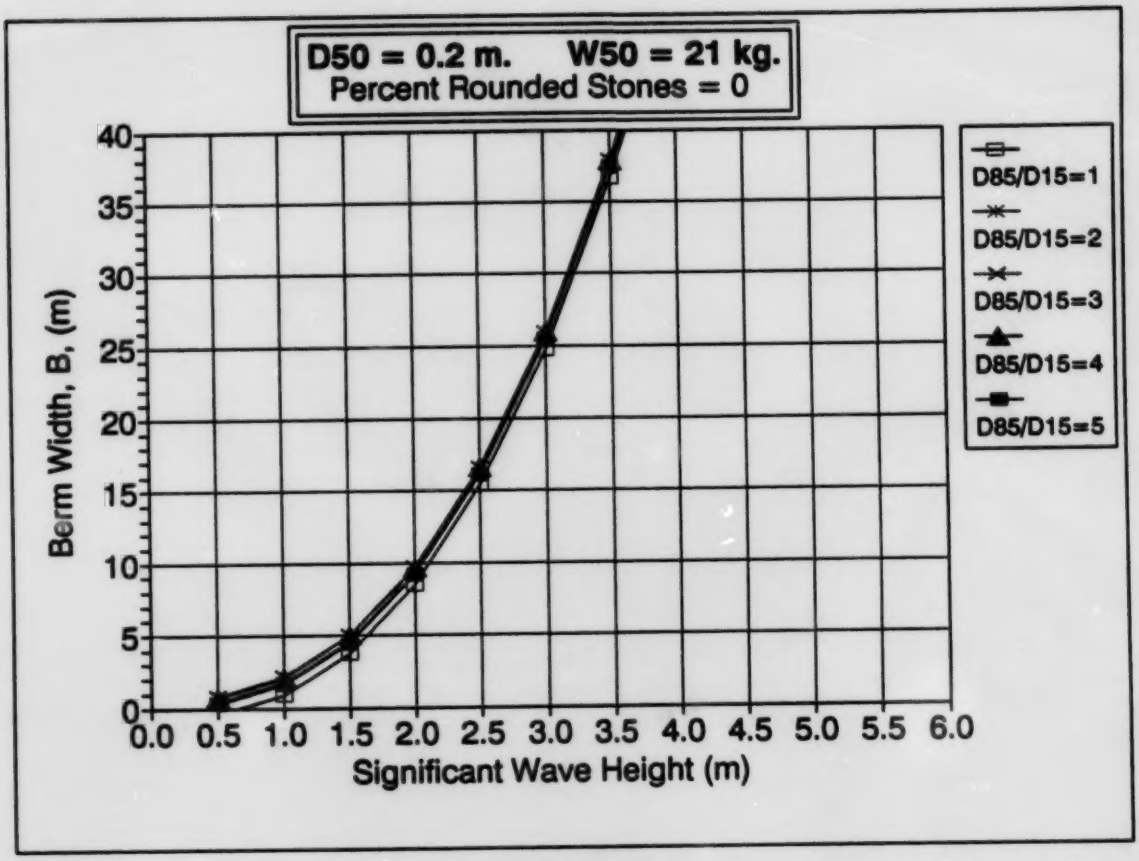
Baird, W.F. and Hall, K.R. (1984) "The Design of Breakwaters Using Quarried Stone", Int. Conf. on Coastal Engineering, A.S.C.E. Vol III, p. 2713.

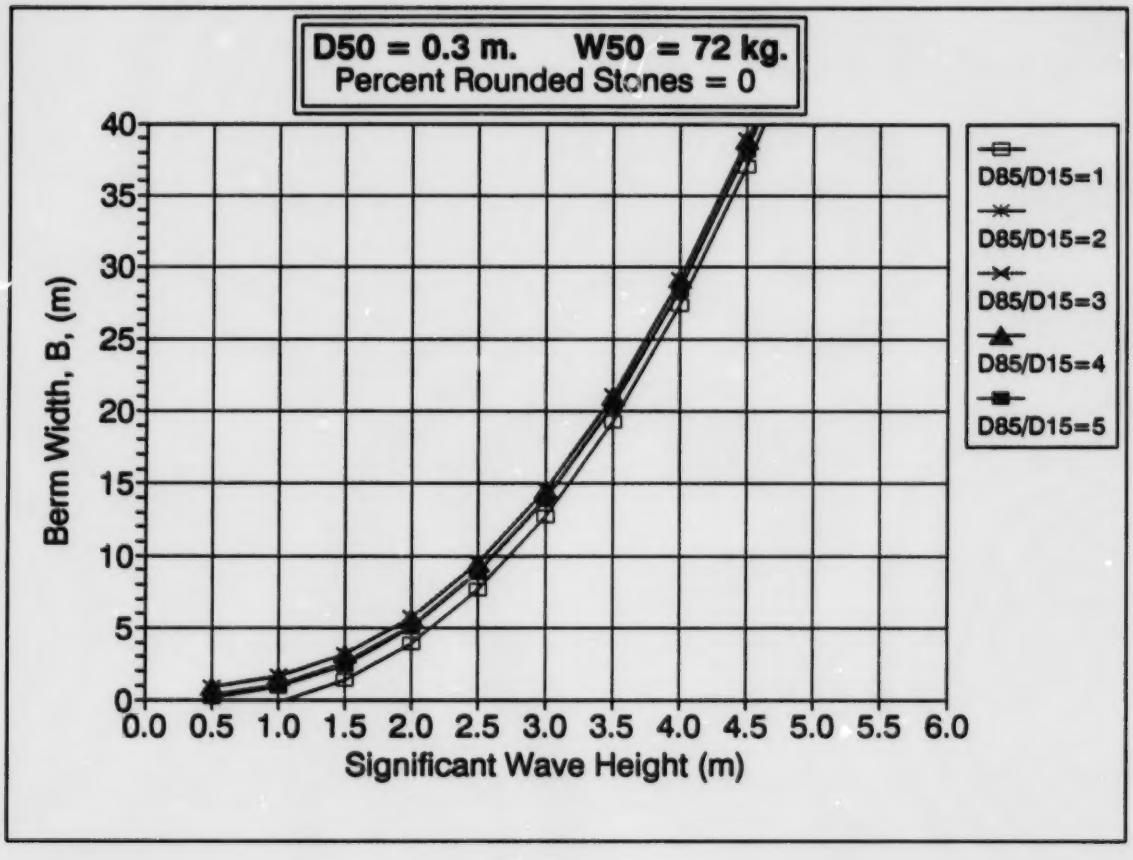
Fookes, P.G. and Poole, A.B., "Some Preliminary Considerations on the Selection and Durability of Materials for Breakwaters and Coastal Protection", Q.J. Eng. Geol., London, Vol. 14, pp. 97-128.

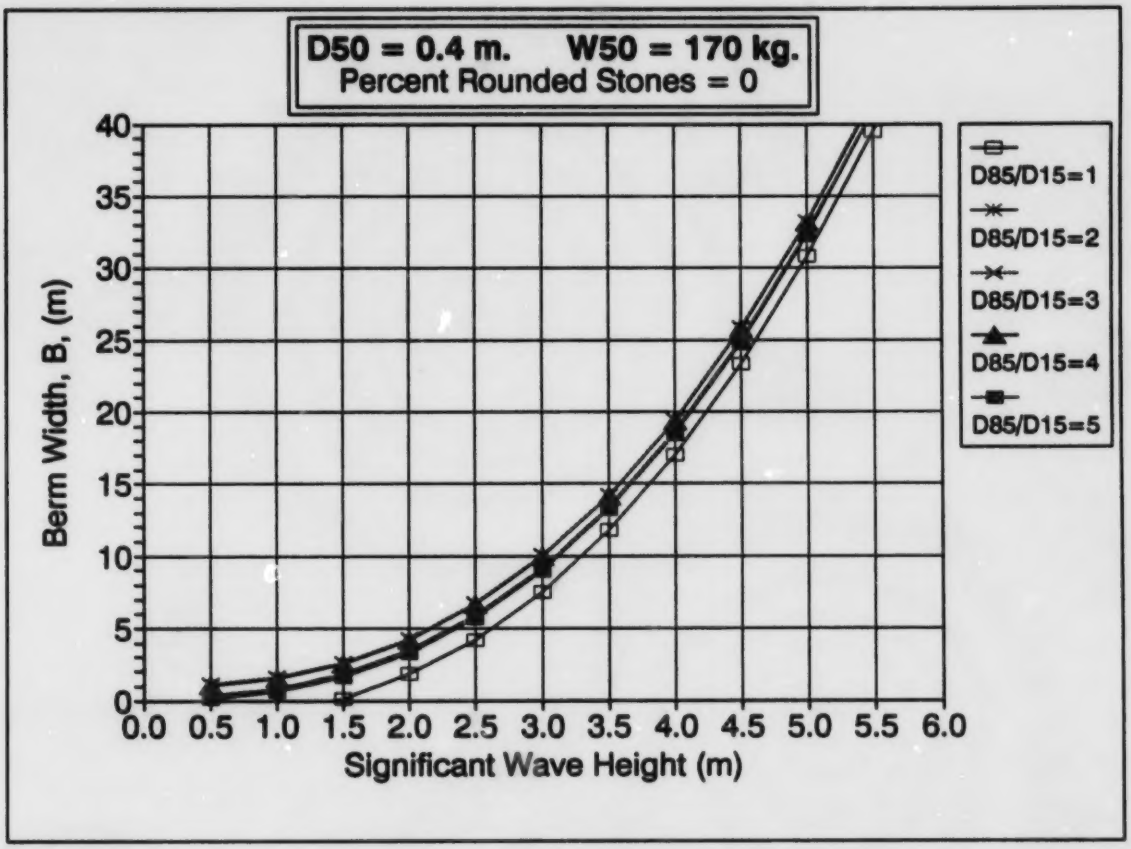
APPENDIX A

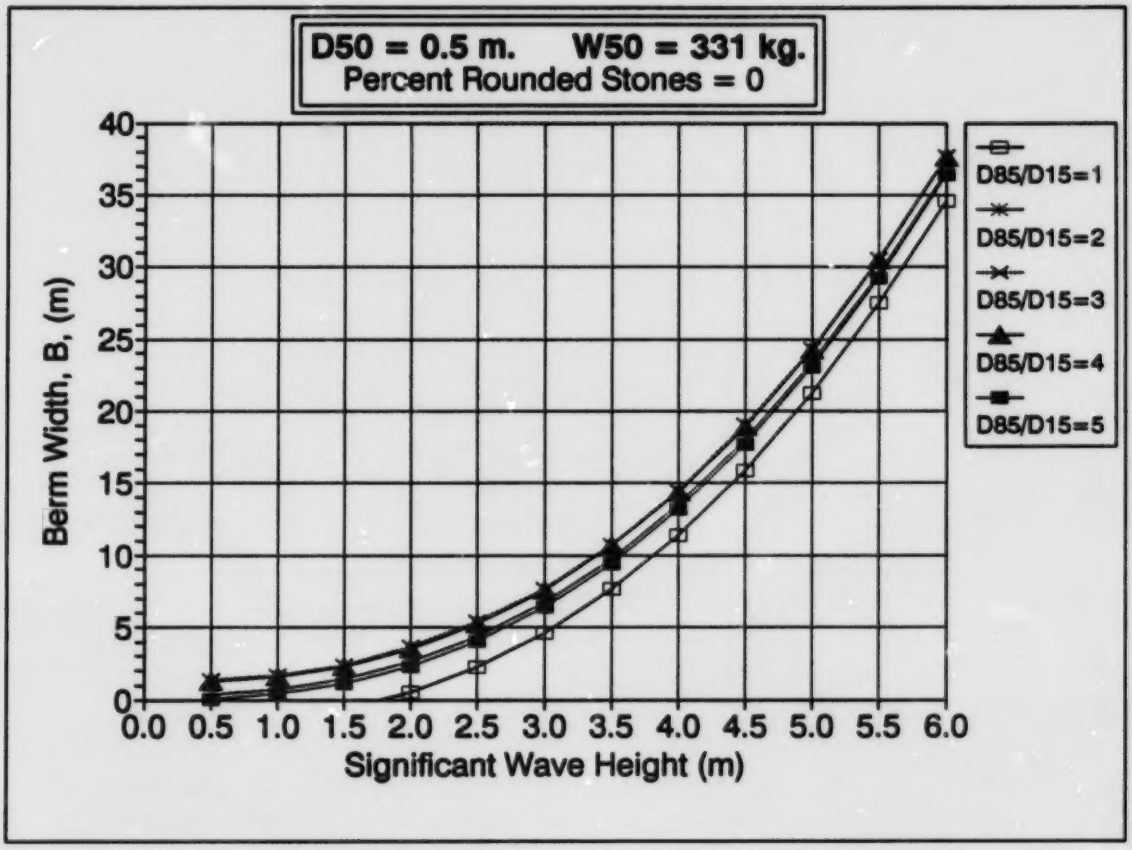
Design Charts

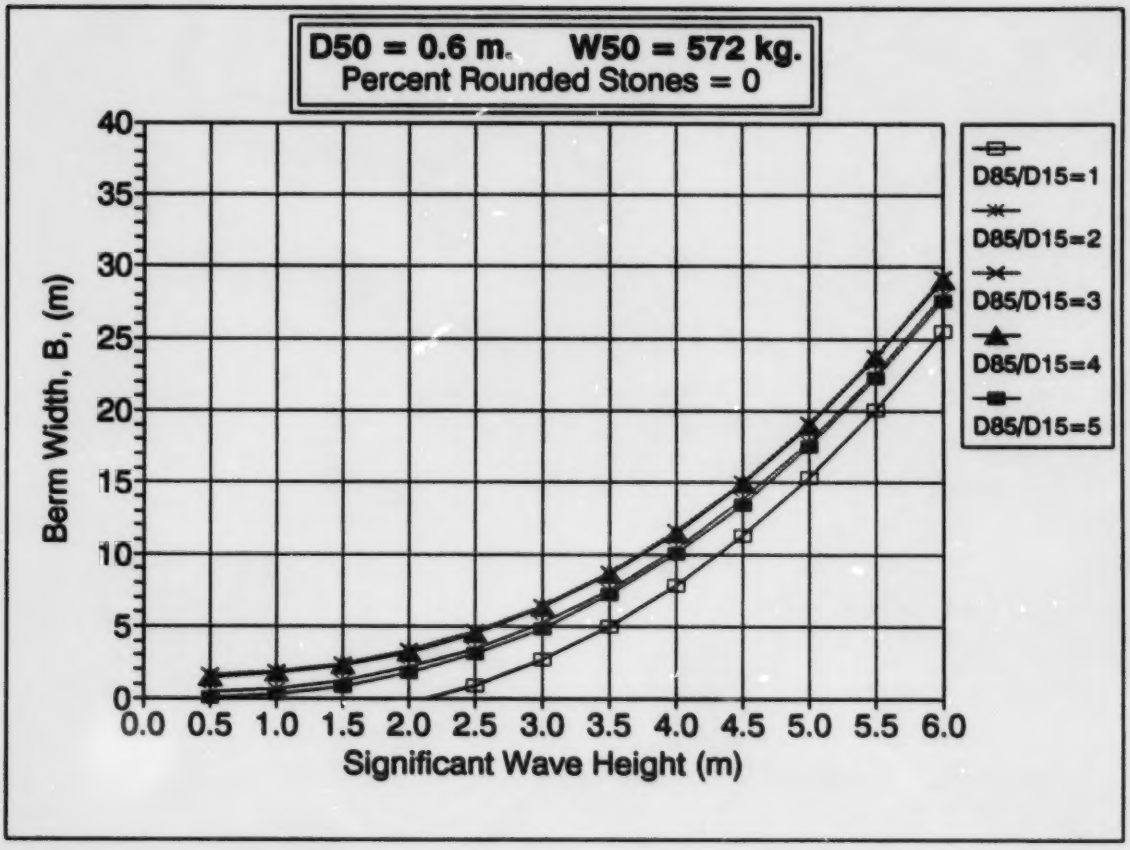

D50 = 0.1 m. W50 = 3 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

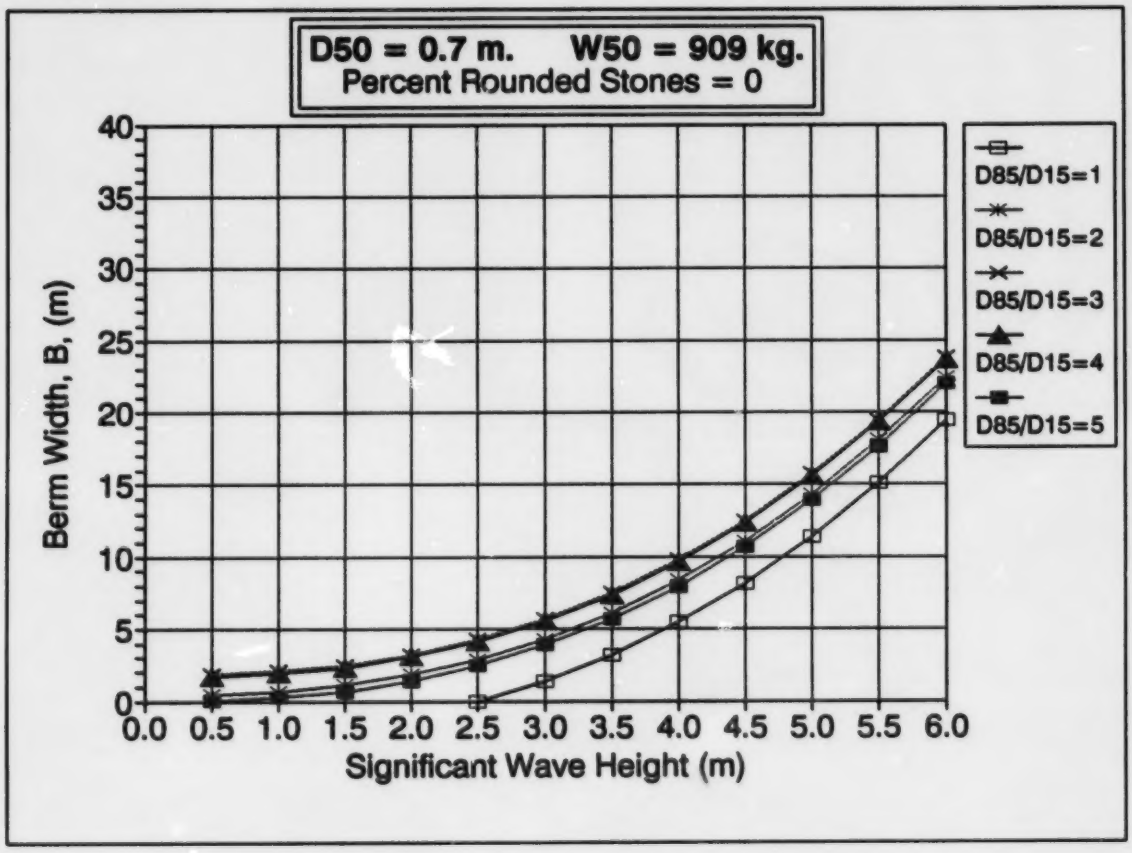

D50 = 0.2 m. W50 = 21 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

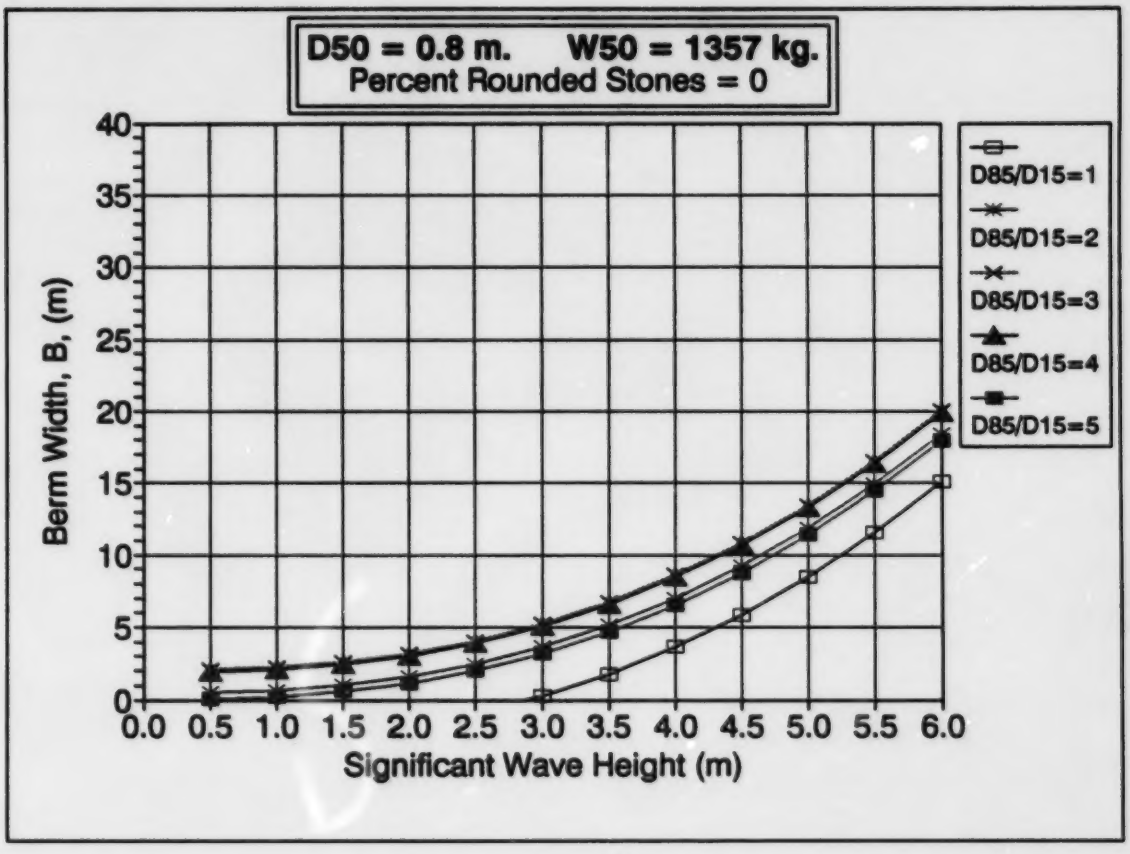

D50 = 0.3 m. W50 = 72 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

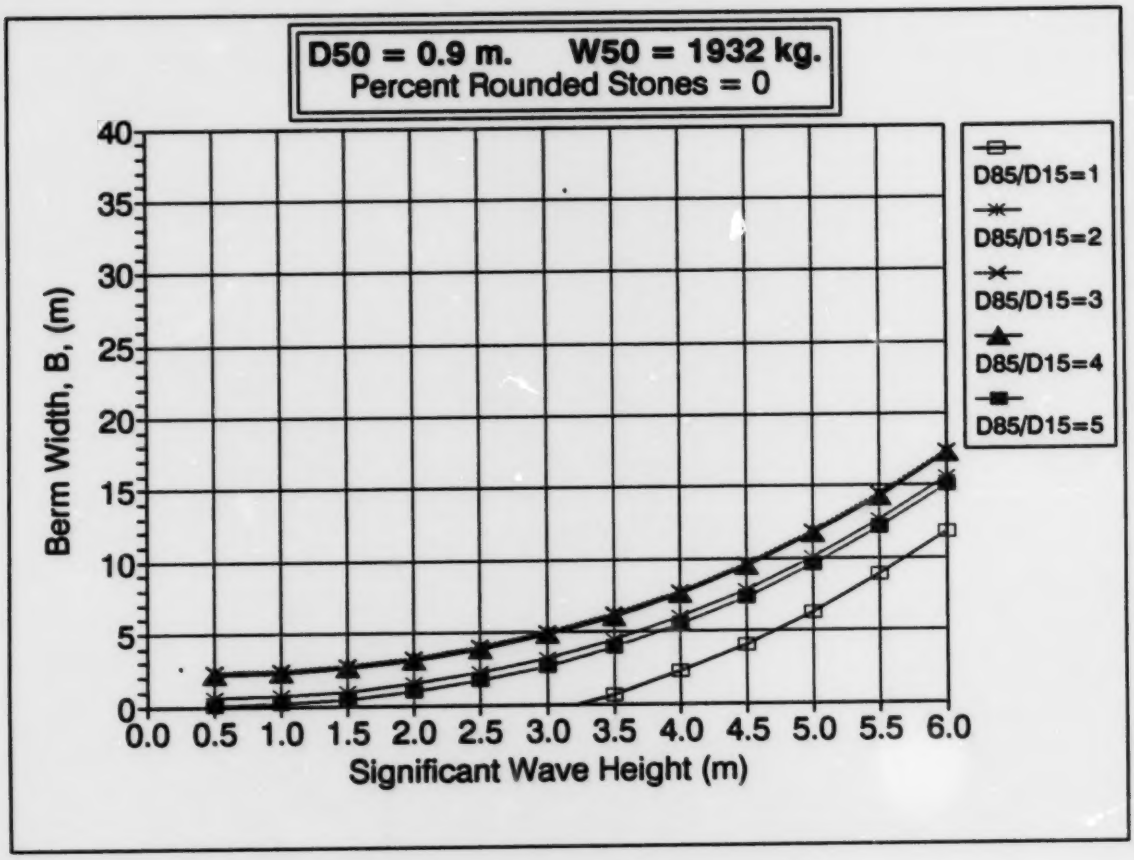

D50 = 0.4 m. W50 = 170 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

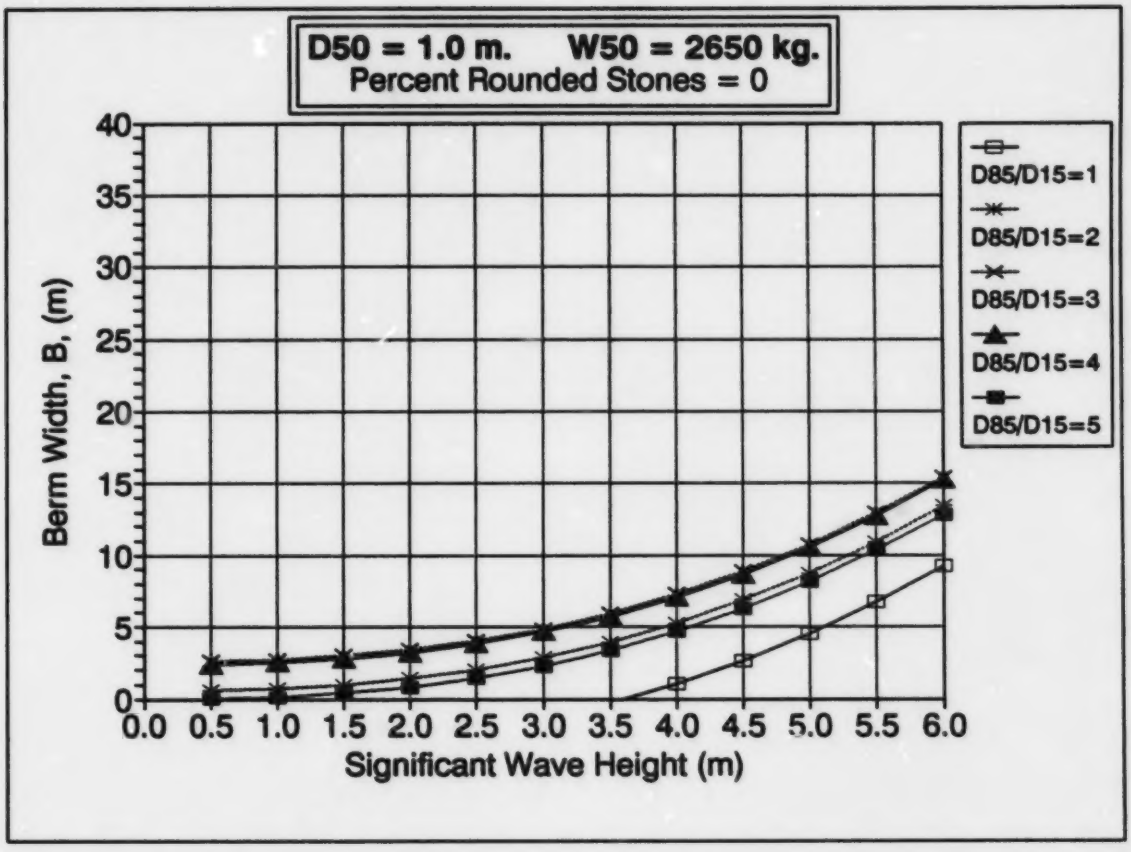

D50 = 0.5 m. W50 = 331 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

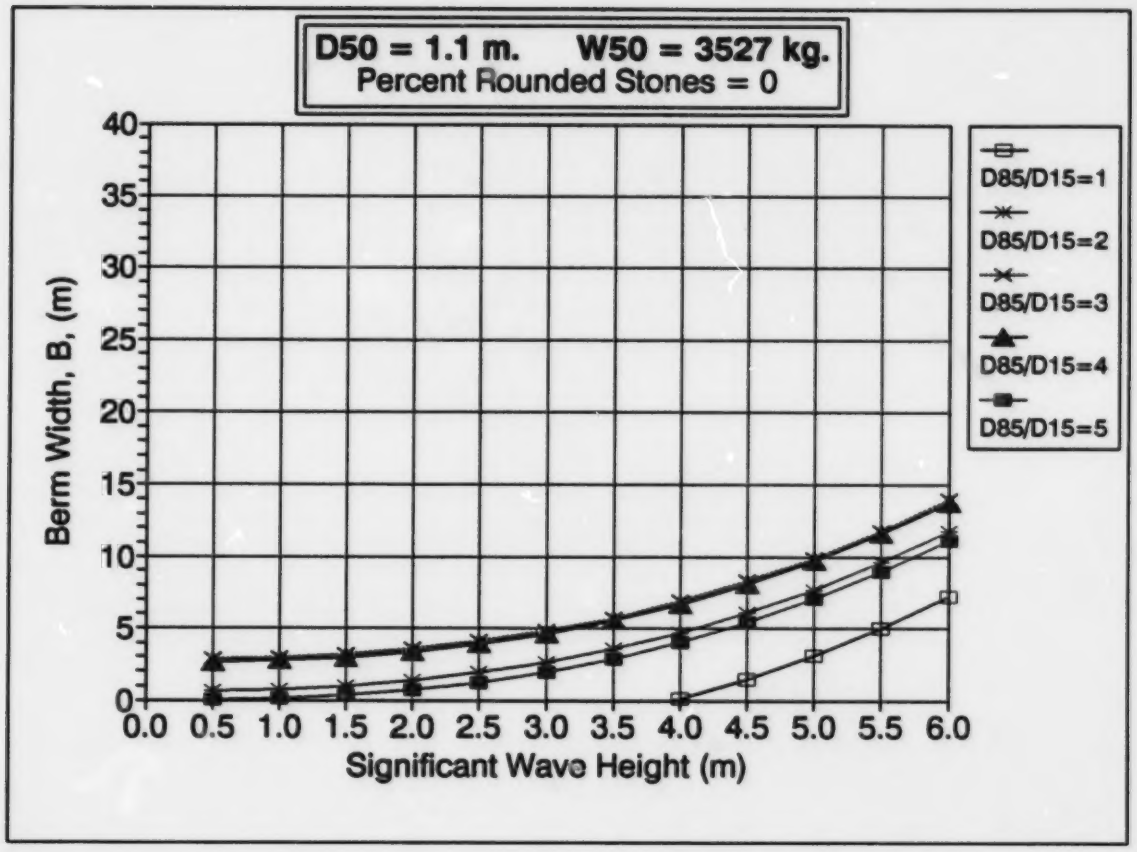

D50 = 0.6 m. W50 = 572 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

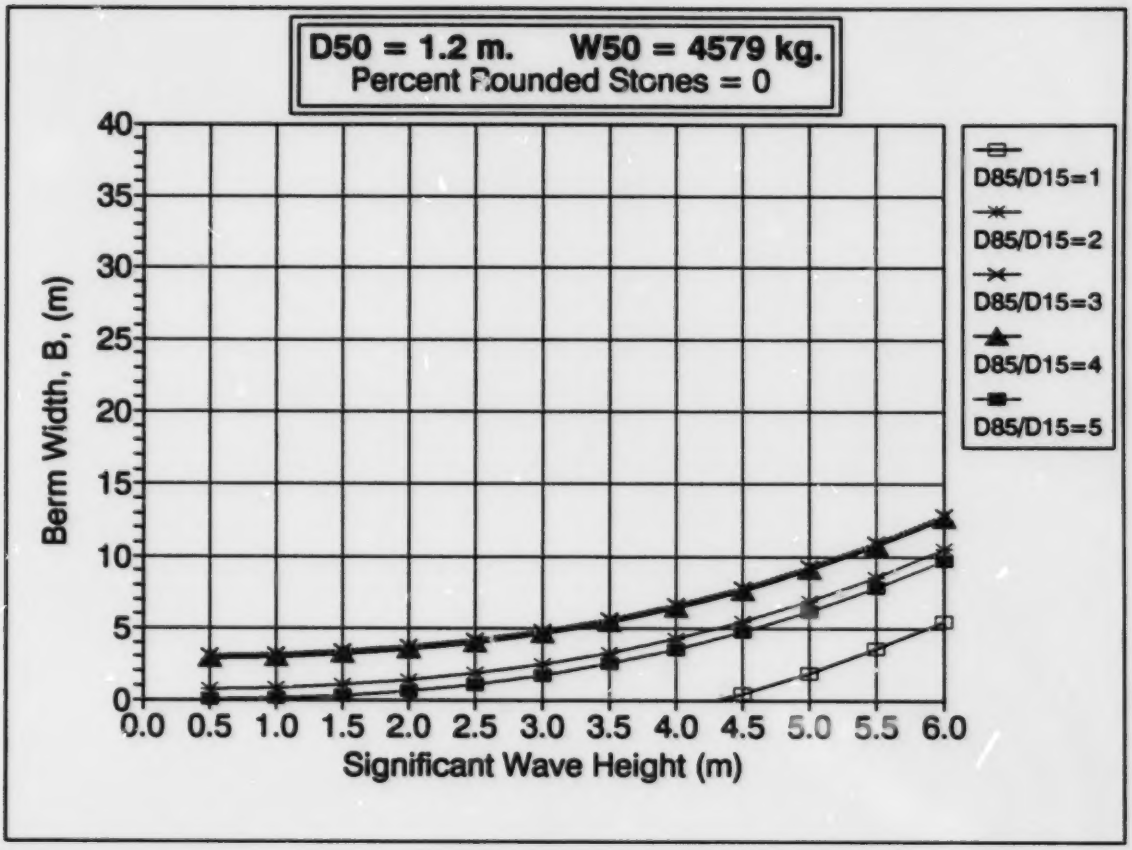

D50 = 0.7 m. W50 = 909 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

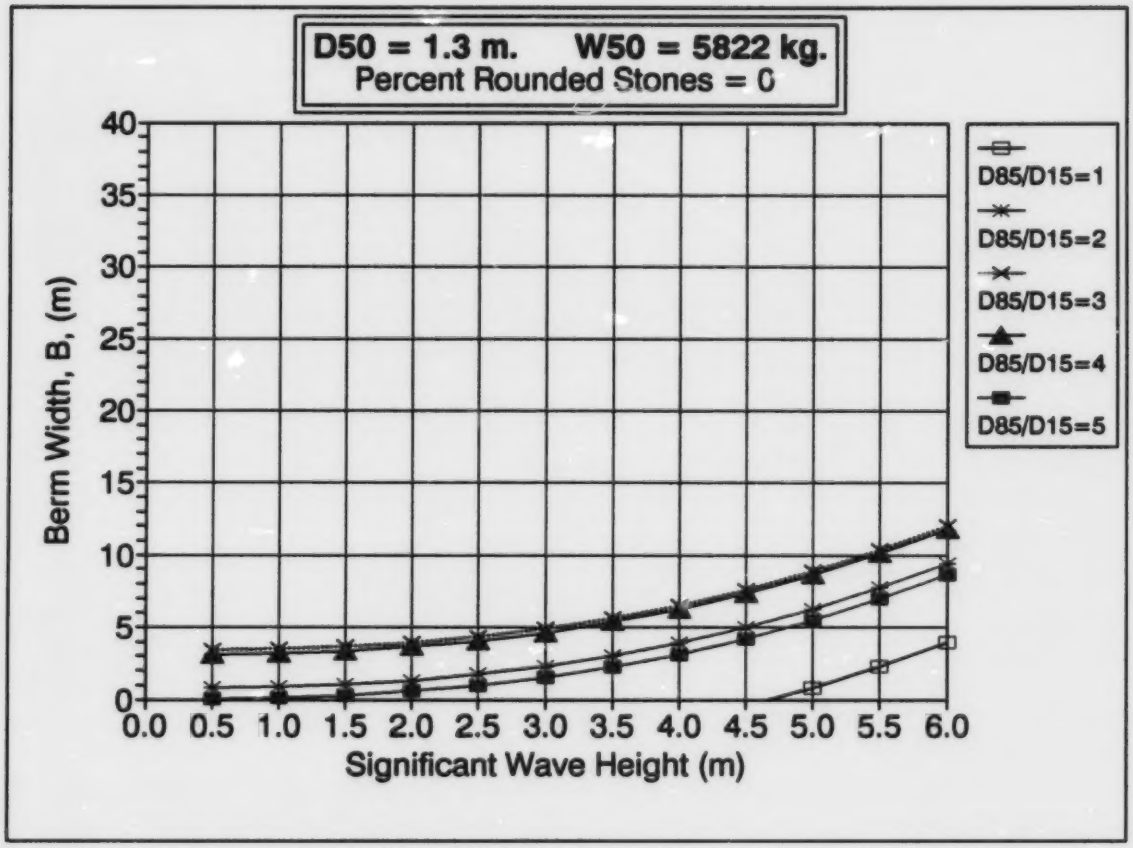

D50 = 0.8 m. W50 = 1357 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

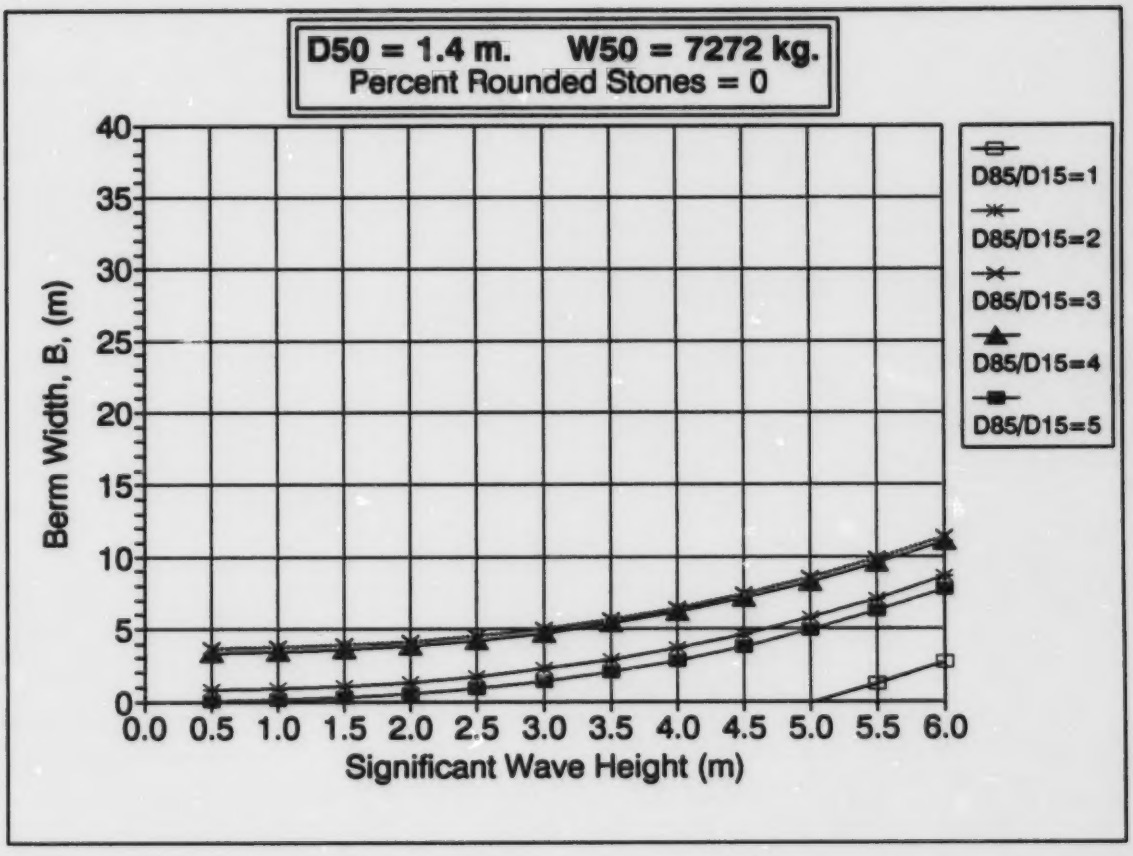

D50 = 0.9 m. W50 = 1932 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

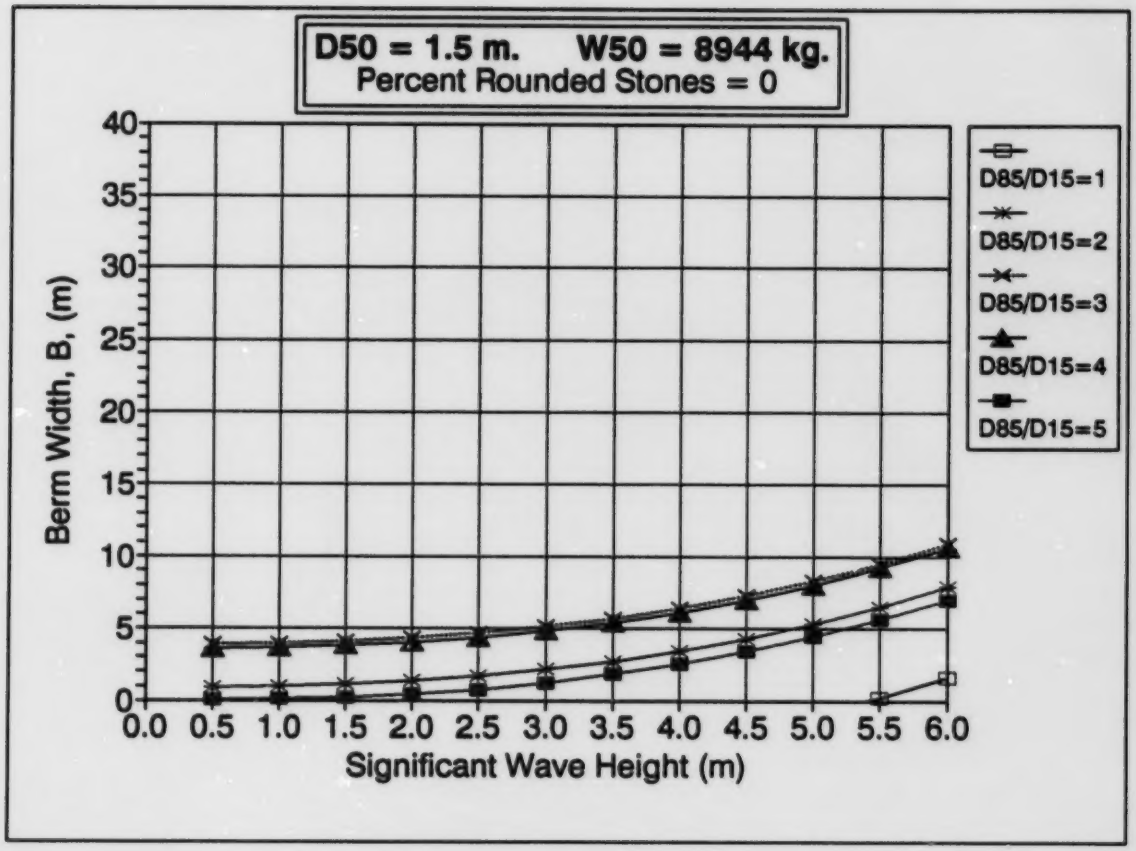

D50 = 1.0 m. W50 = 2650 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

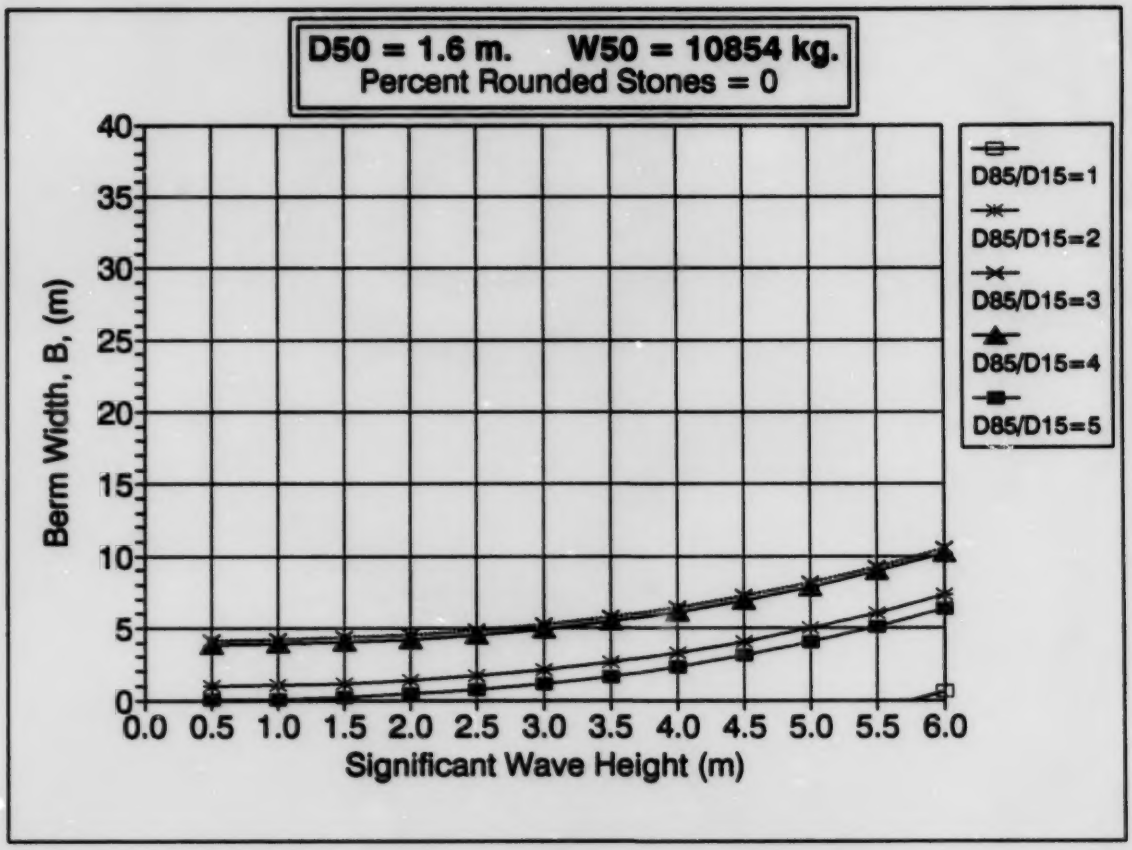

D50 = 1.1 m. W50 = 3527 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

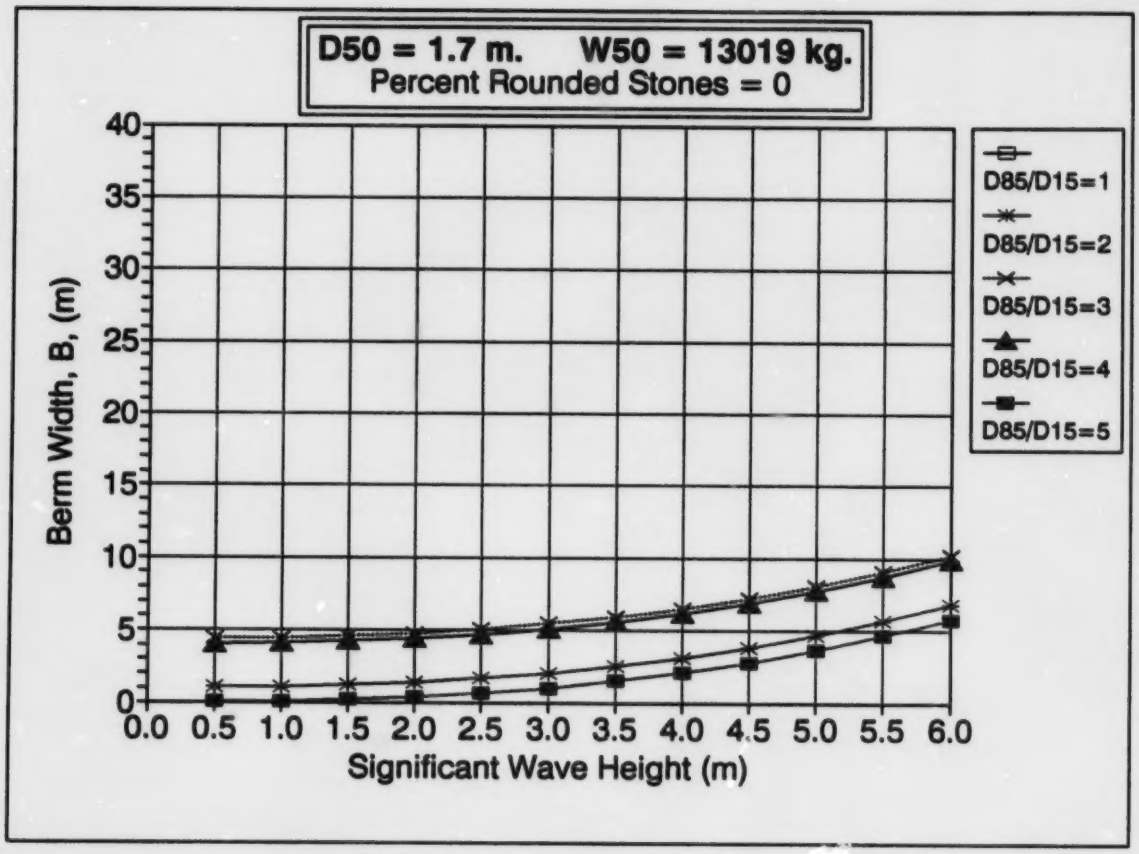

D50 = 1.2 m. W50 = 4579 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

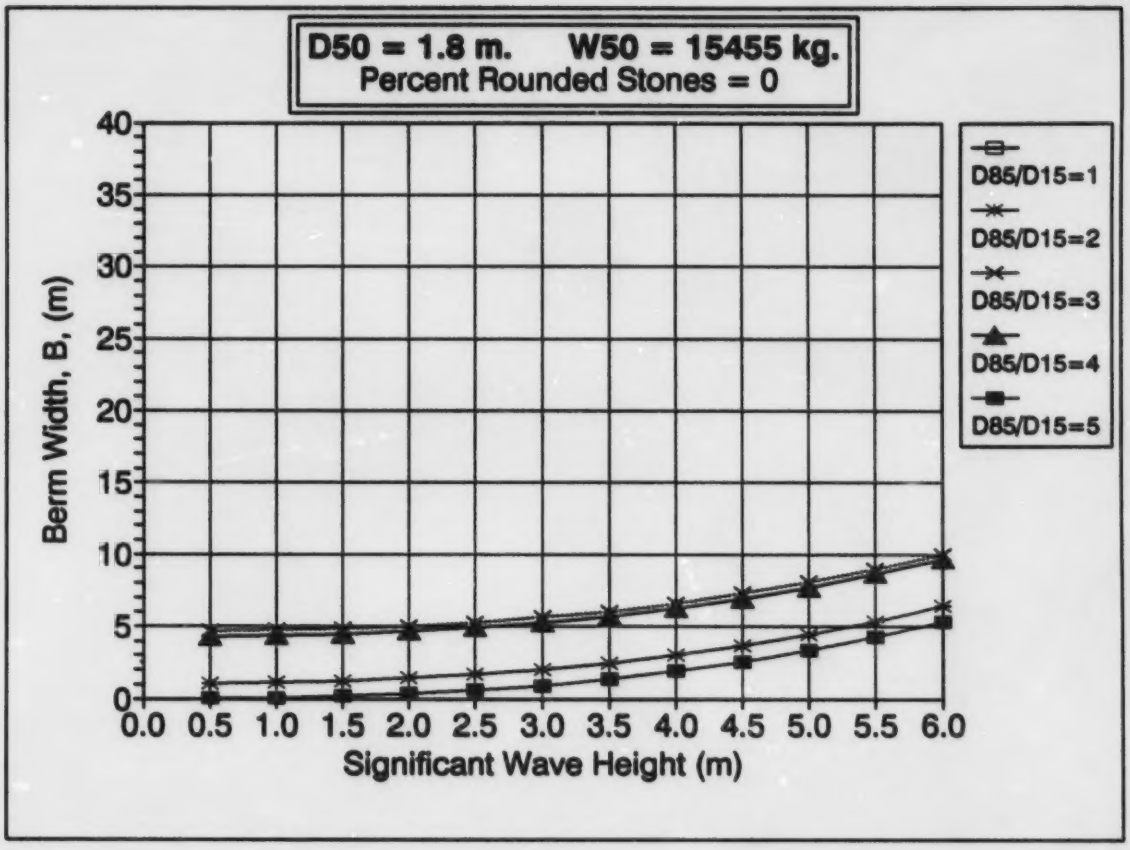

D50 = 1.3 m. W50 = 5822 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

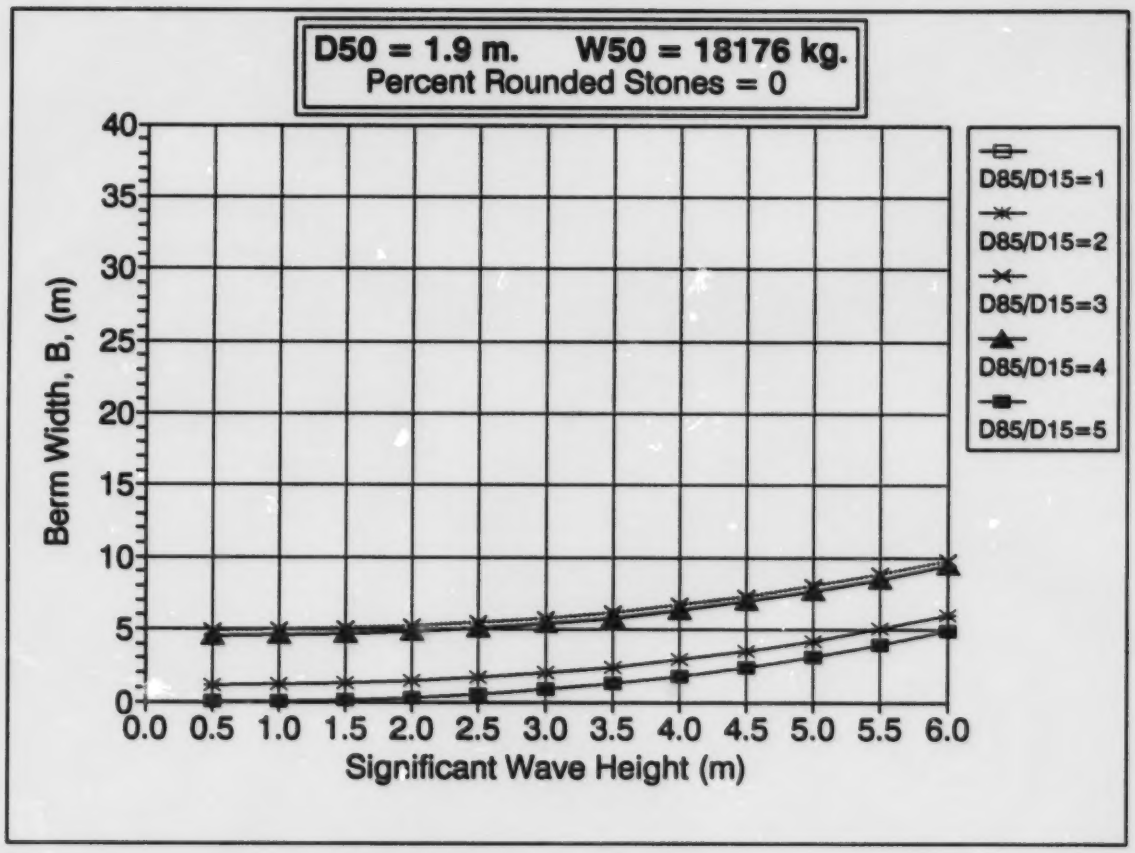

D50 = 1.4 m. W50 = 7272 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

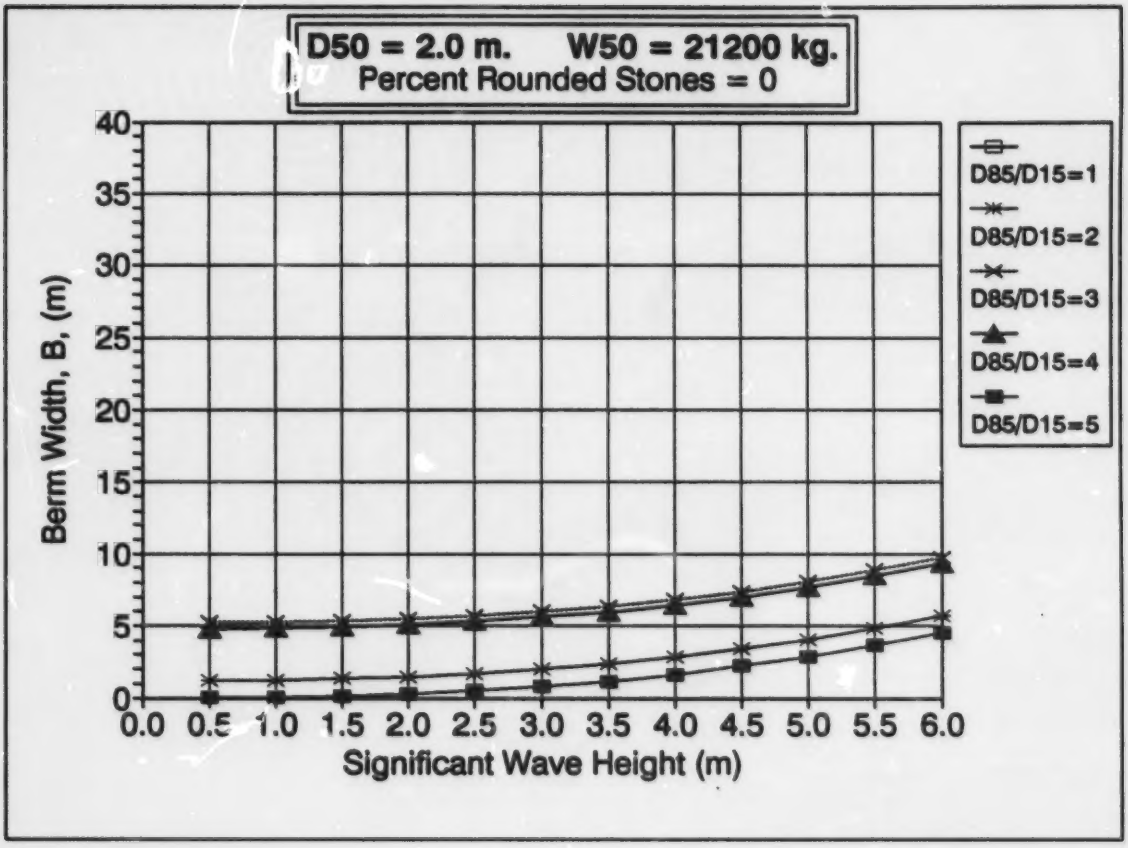

D50 = 1.5 m. W50 = 8944 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

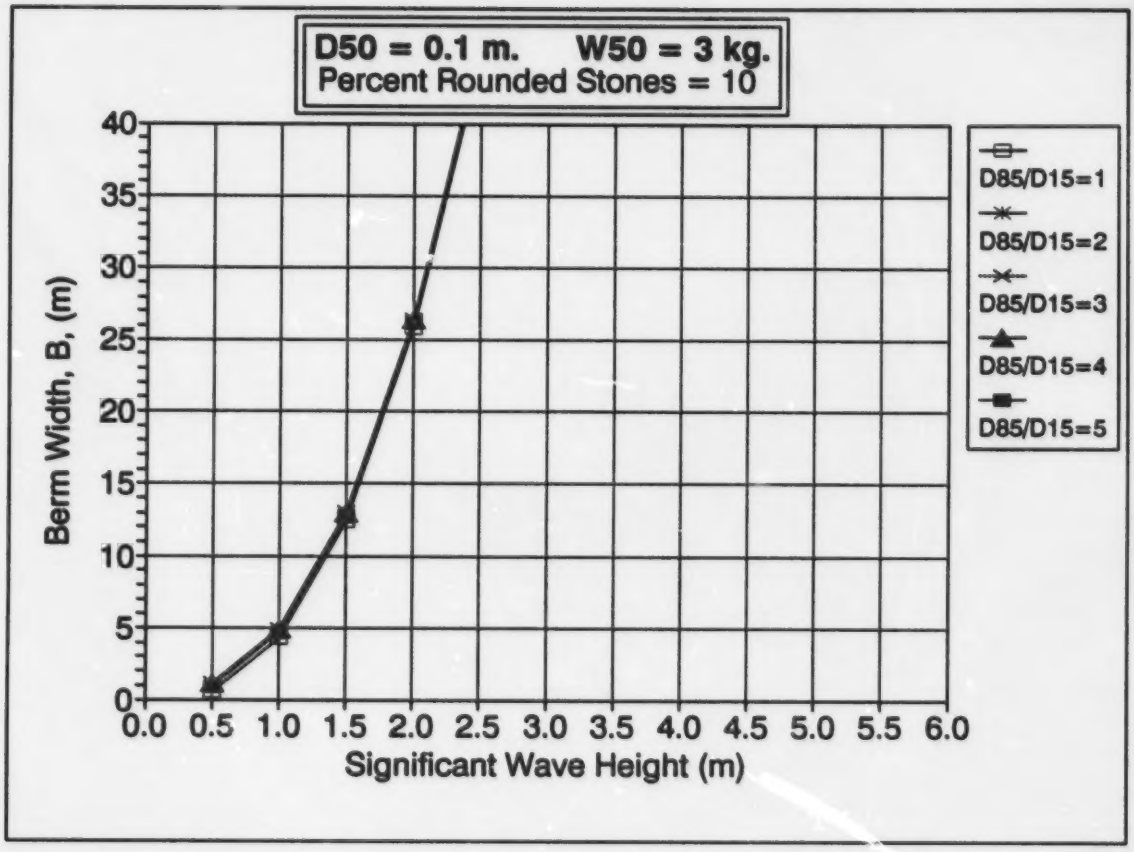

D50 = 1.6 m. W50 = 10854 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

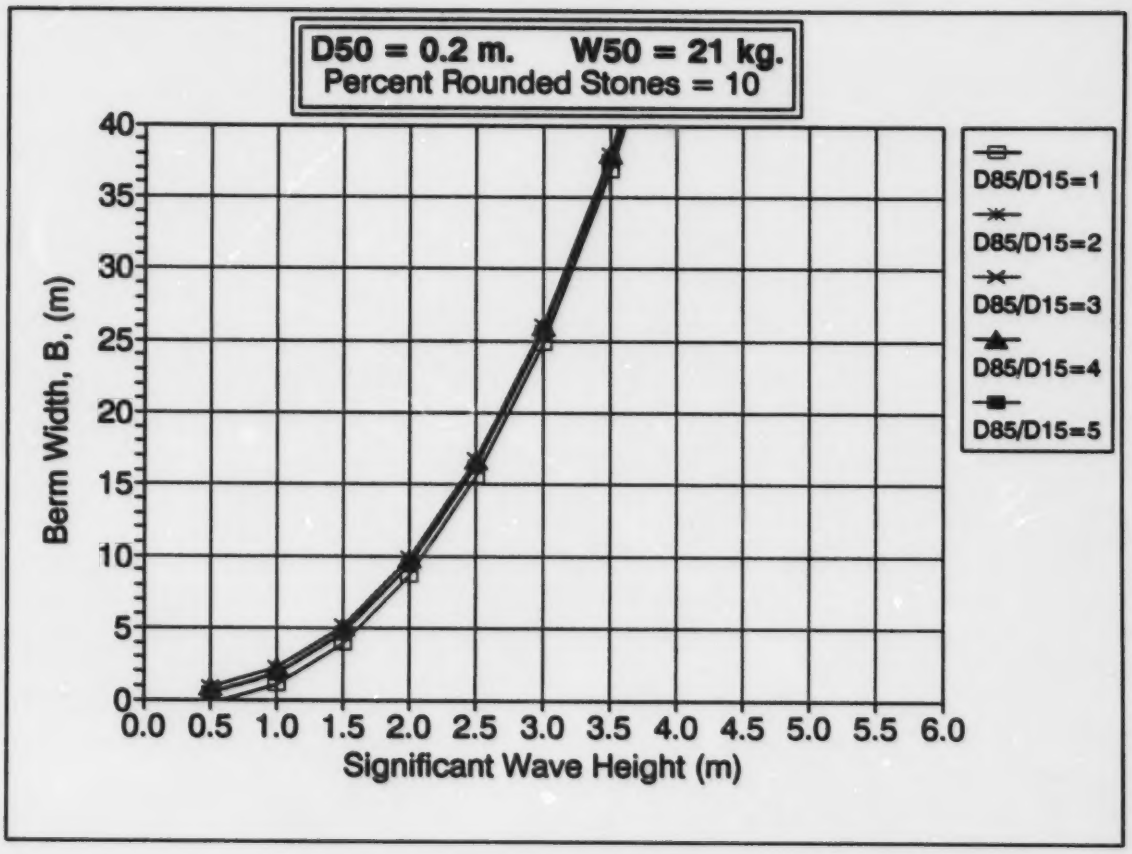

D50 = 1.7 m. W50 = 13019 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

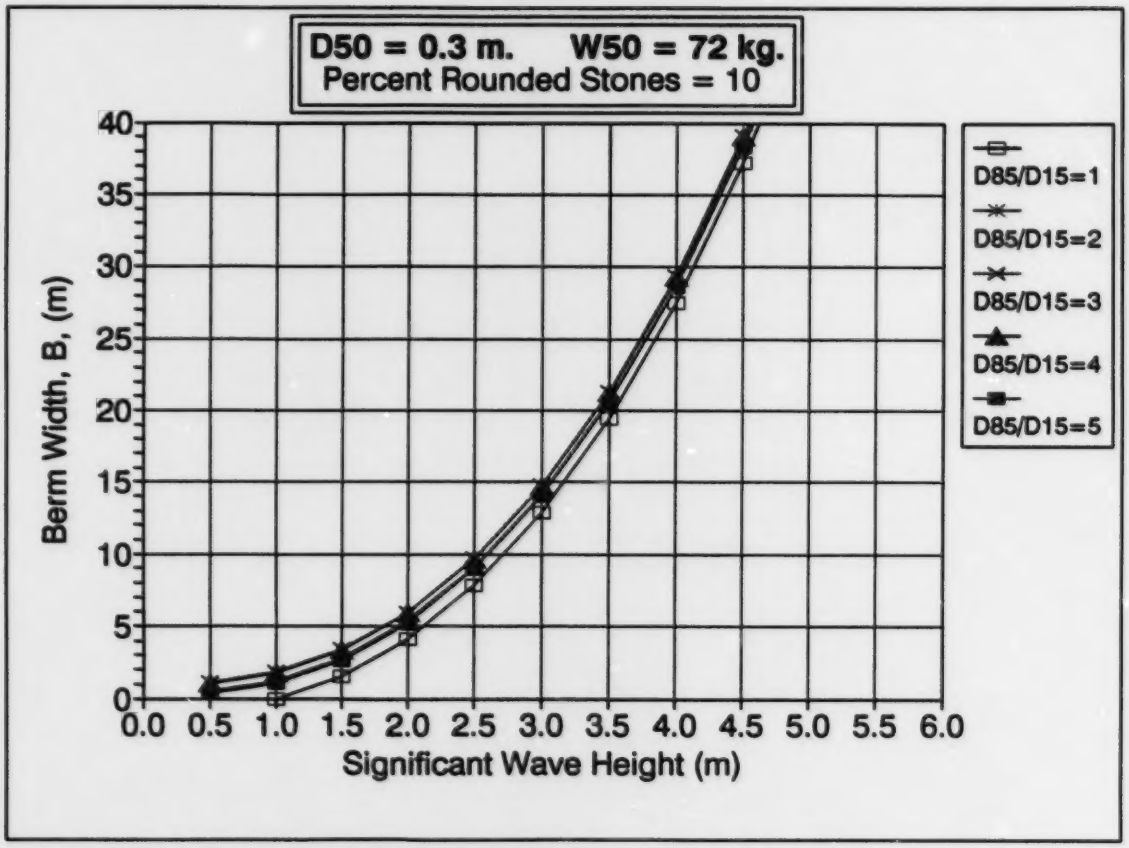

D50 = 1.8 m. W50 = 15455 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

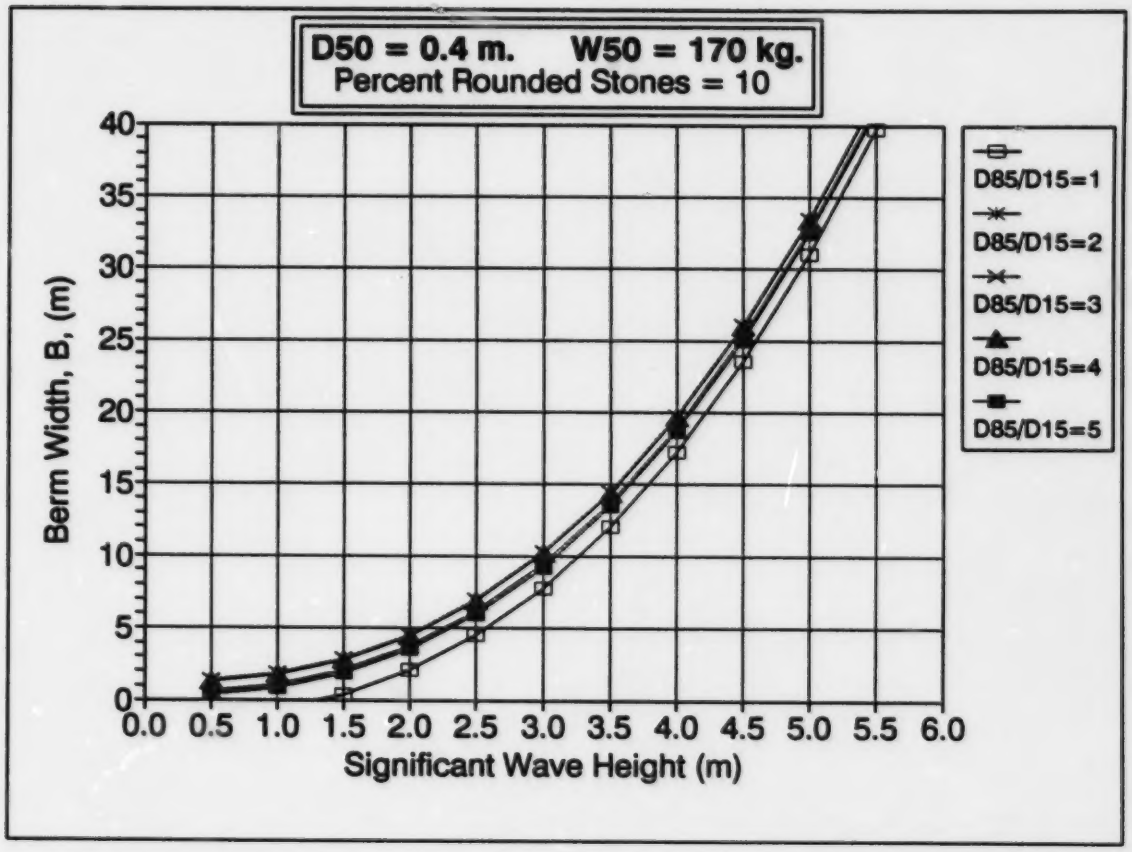

D50 = 1.9 m. W50 = 18176 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

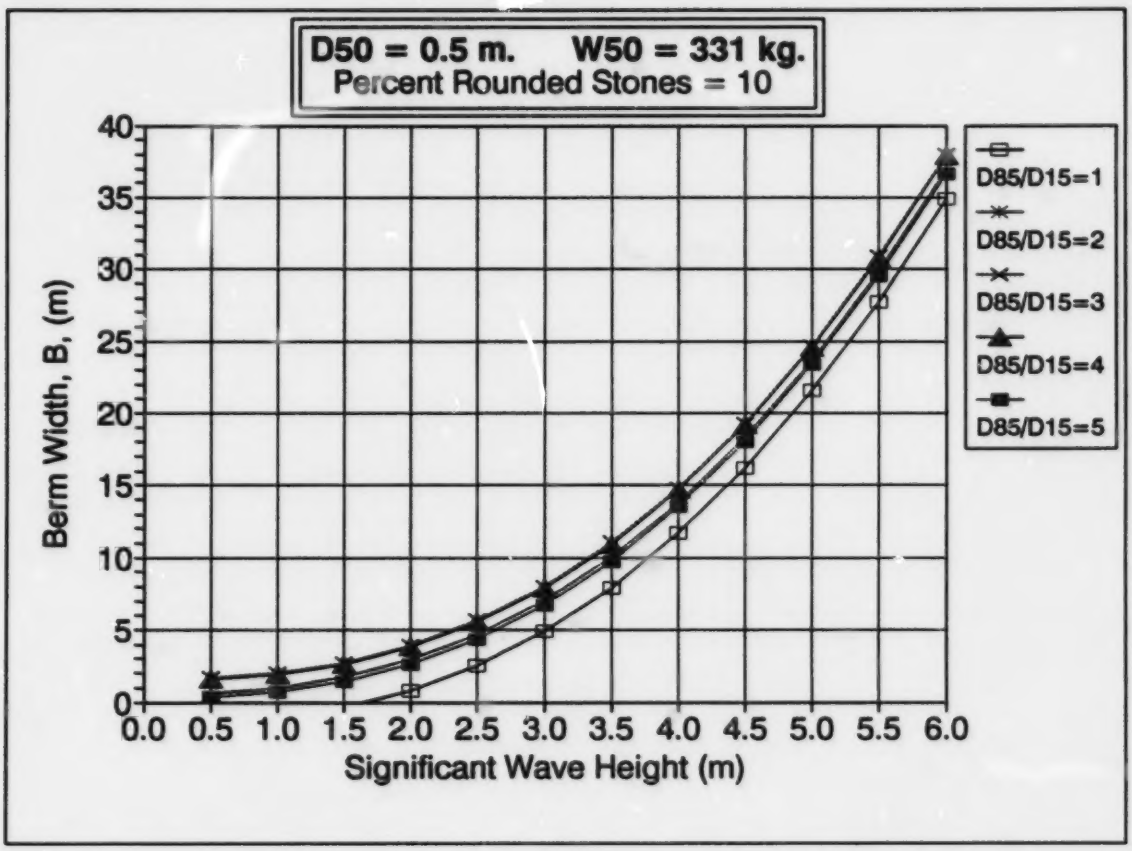

D50 = 2.0 m. W50 = 21200 kg.
Percent Rounded Stones = 0
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

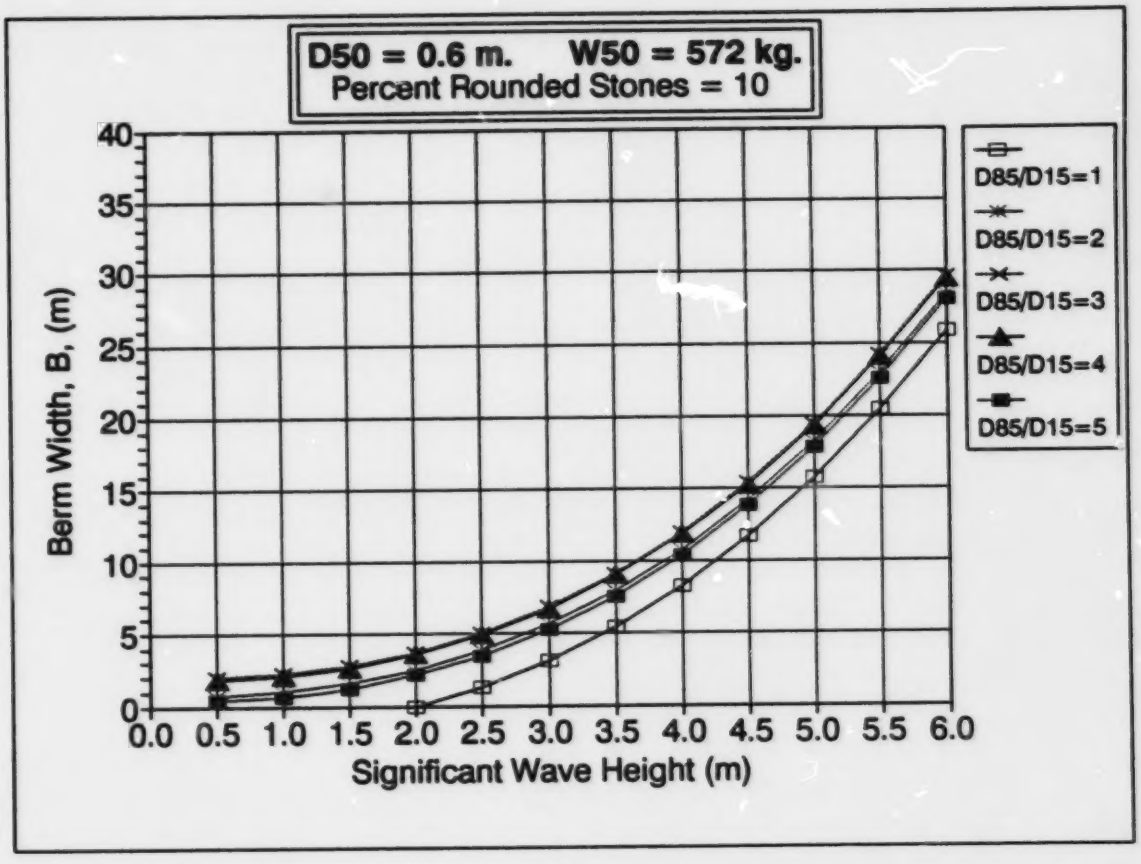

D50 = 0.1 m. W50 = 3 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

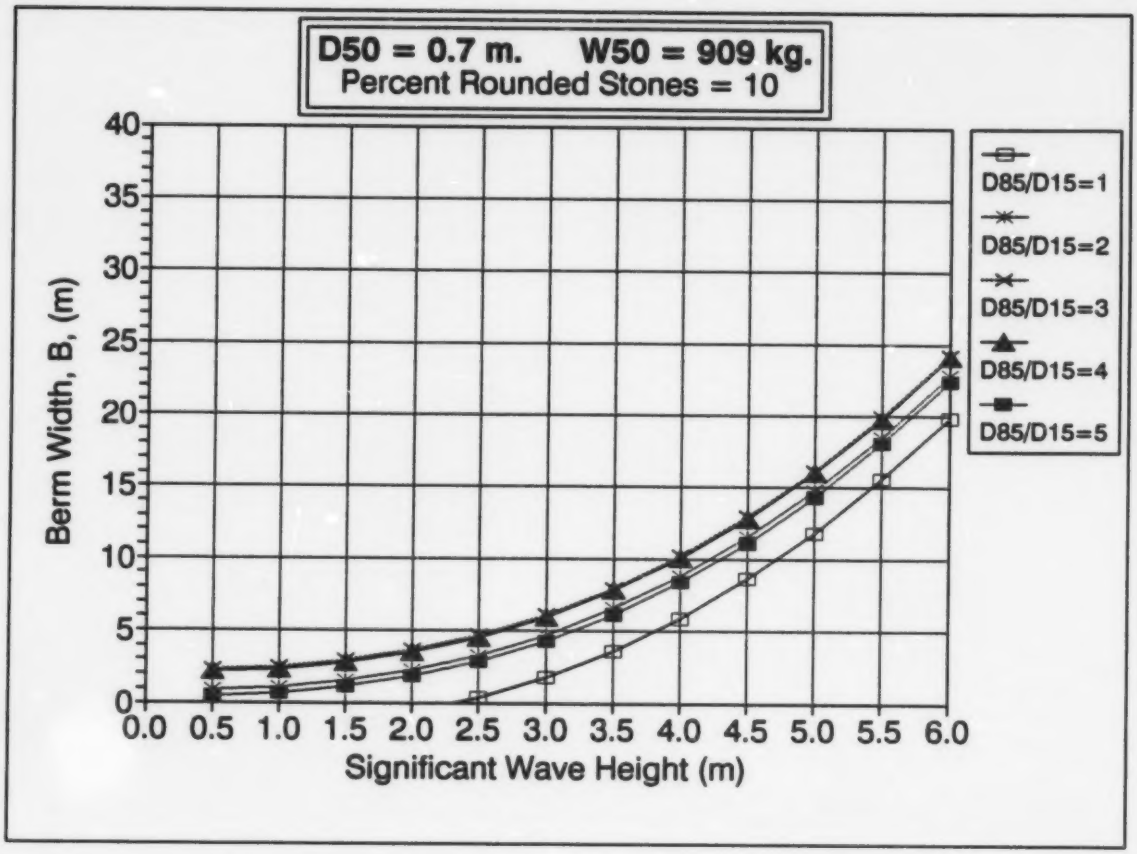

D50 = 0.2 m. W50 = 21 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

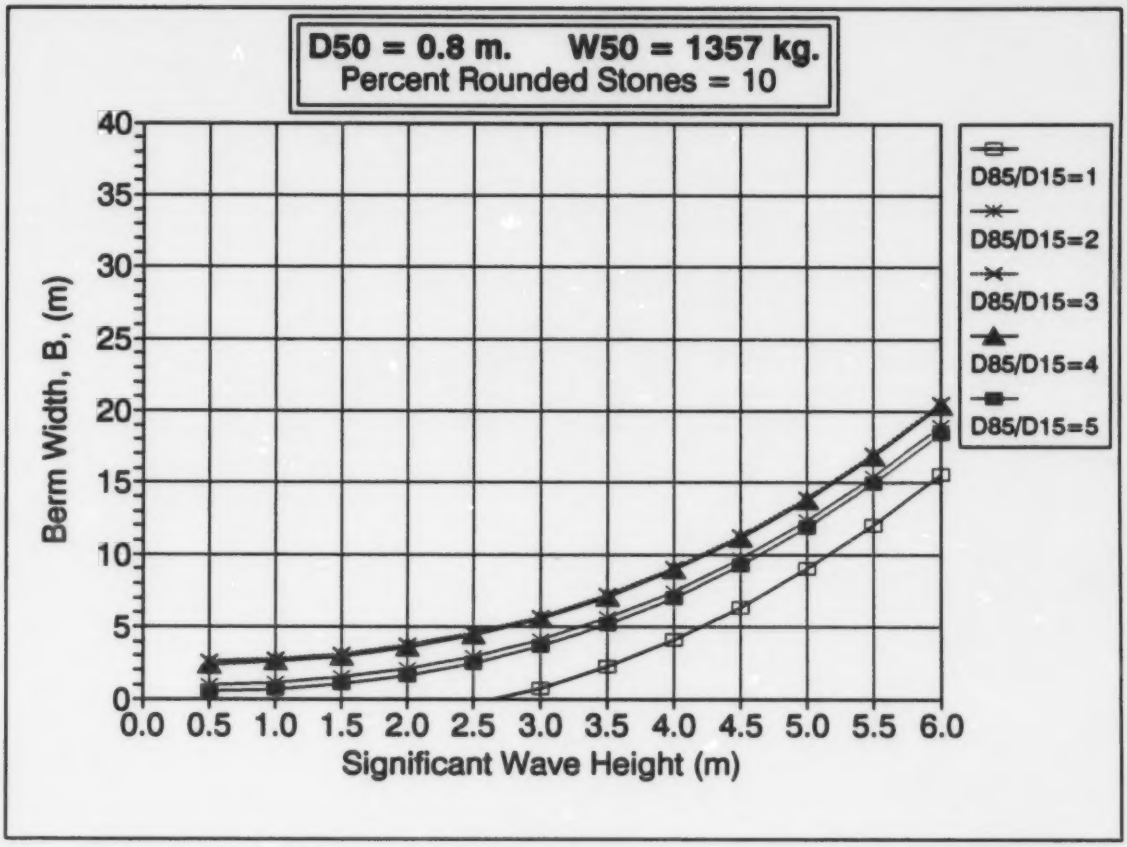

D50 = 0.3 m. W50 = 72 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

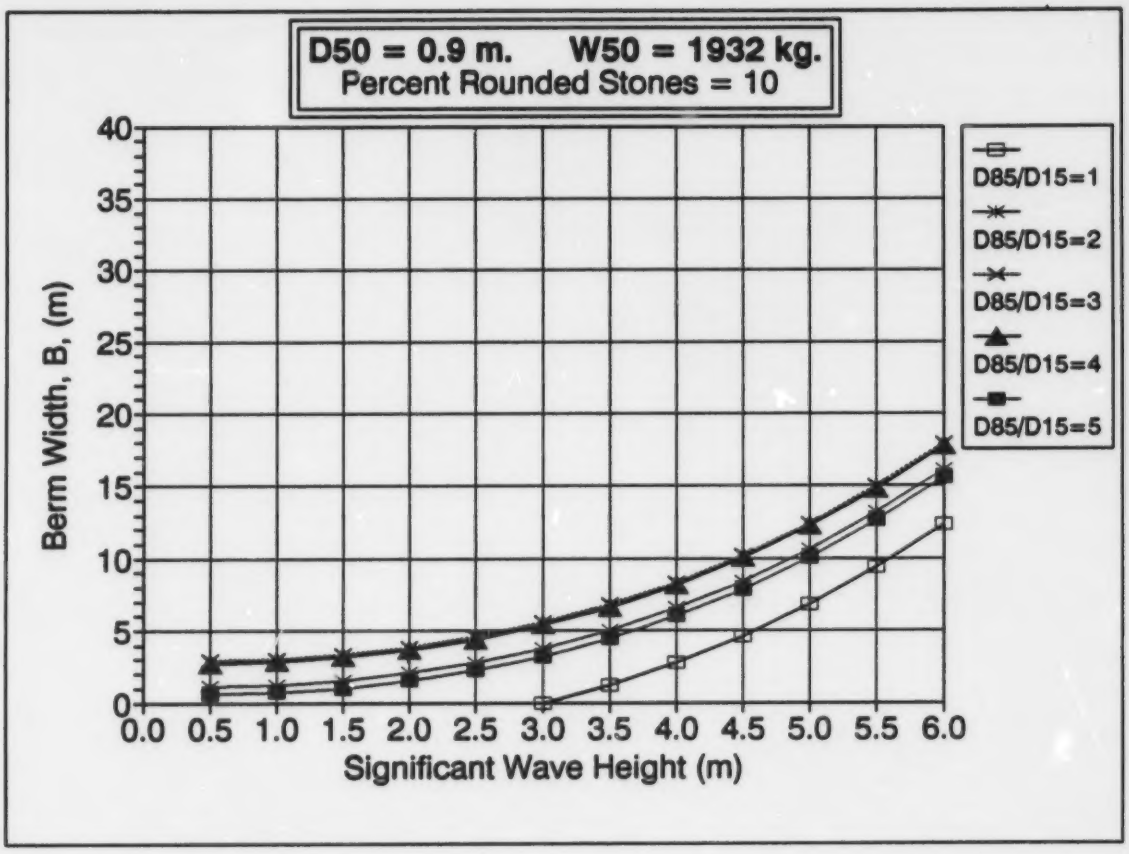

D50 = 0.4 m. W50 = 170 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

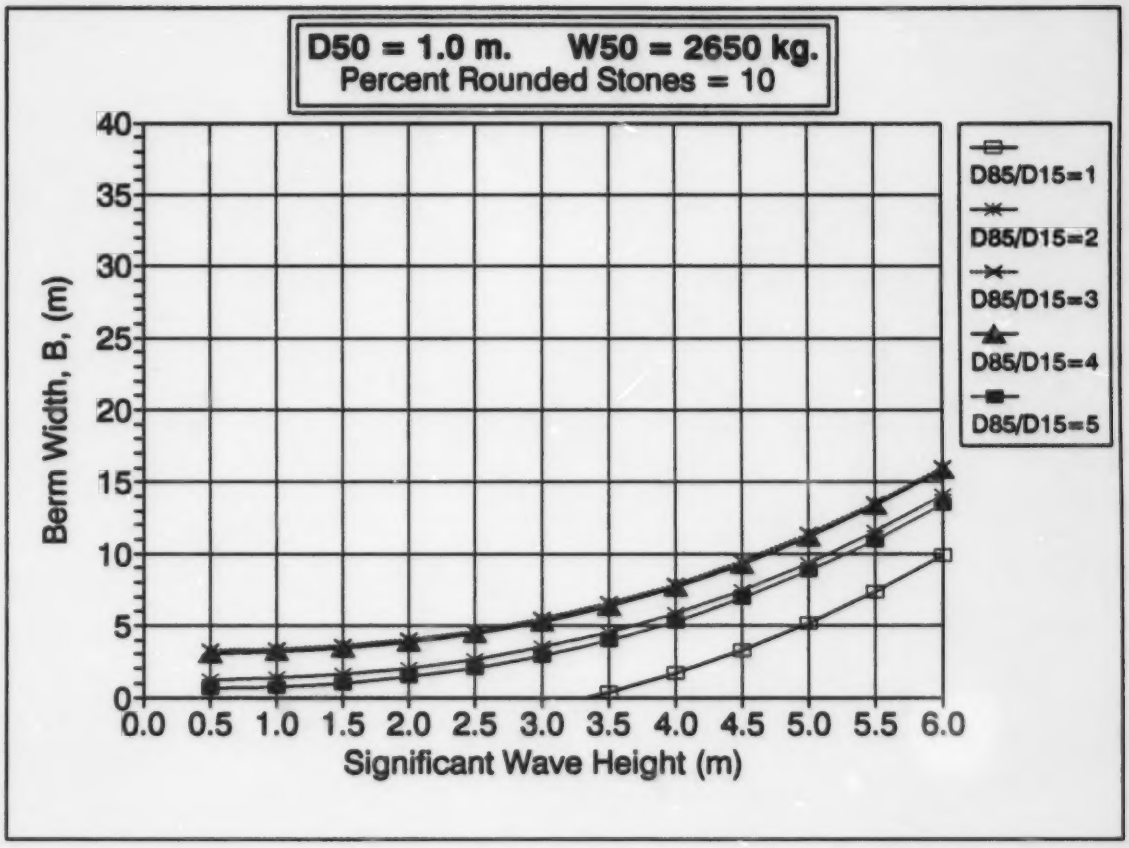

D50 = 0.5 m. W50 = 331 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

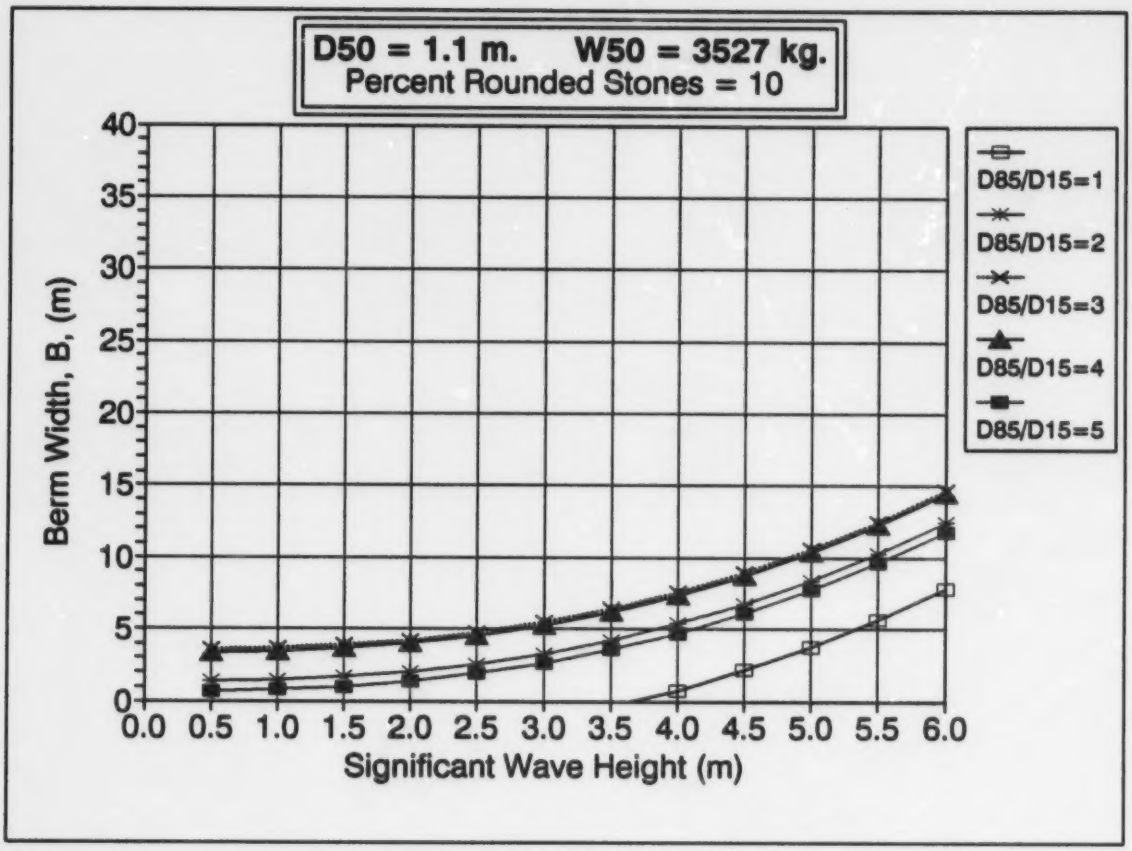

D50 = 0.6 m. W50 = 572 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

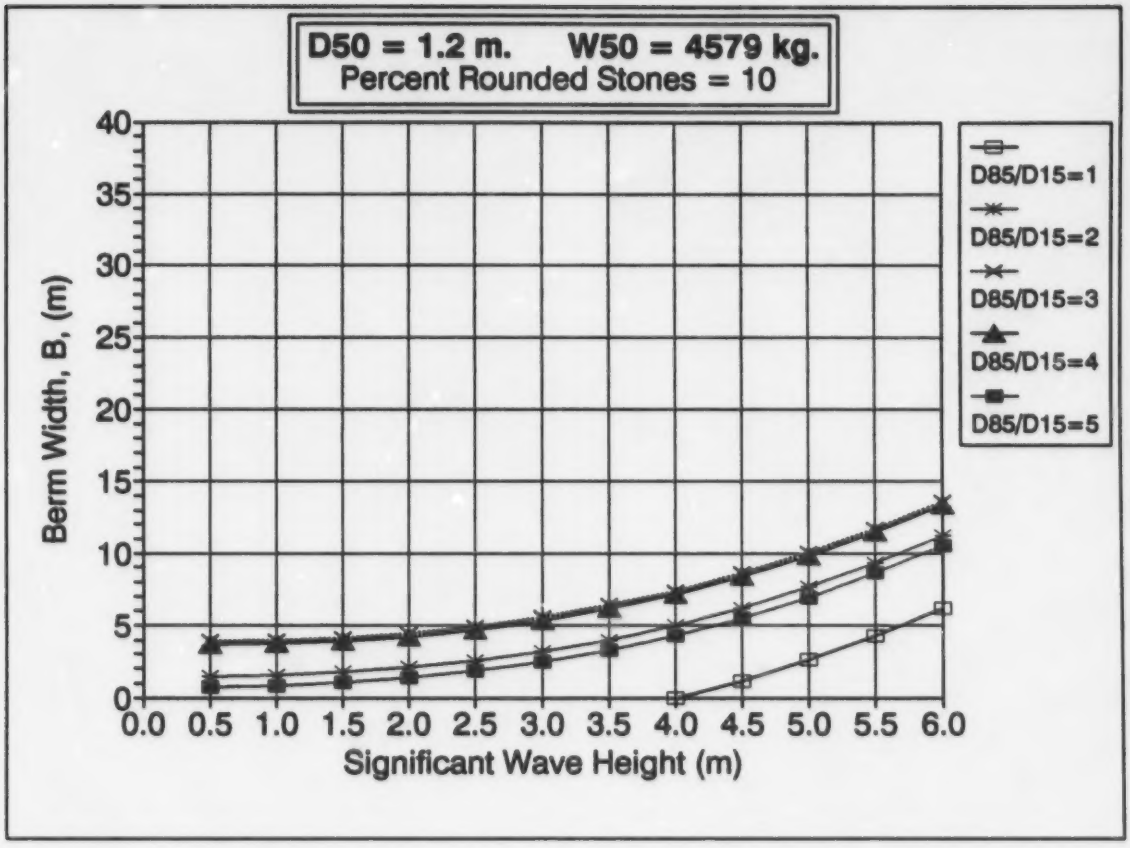

D50 = 0.7 m. W50 = 909 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

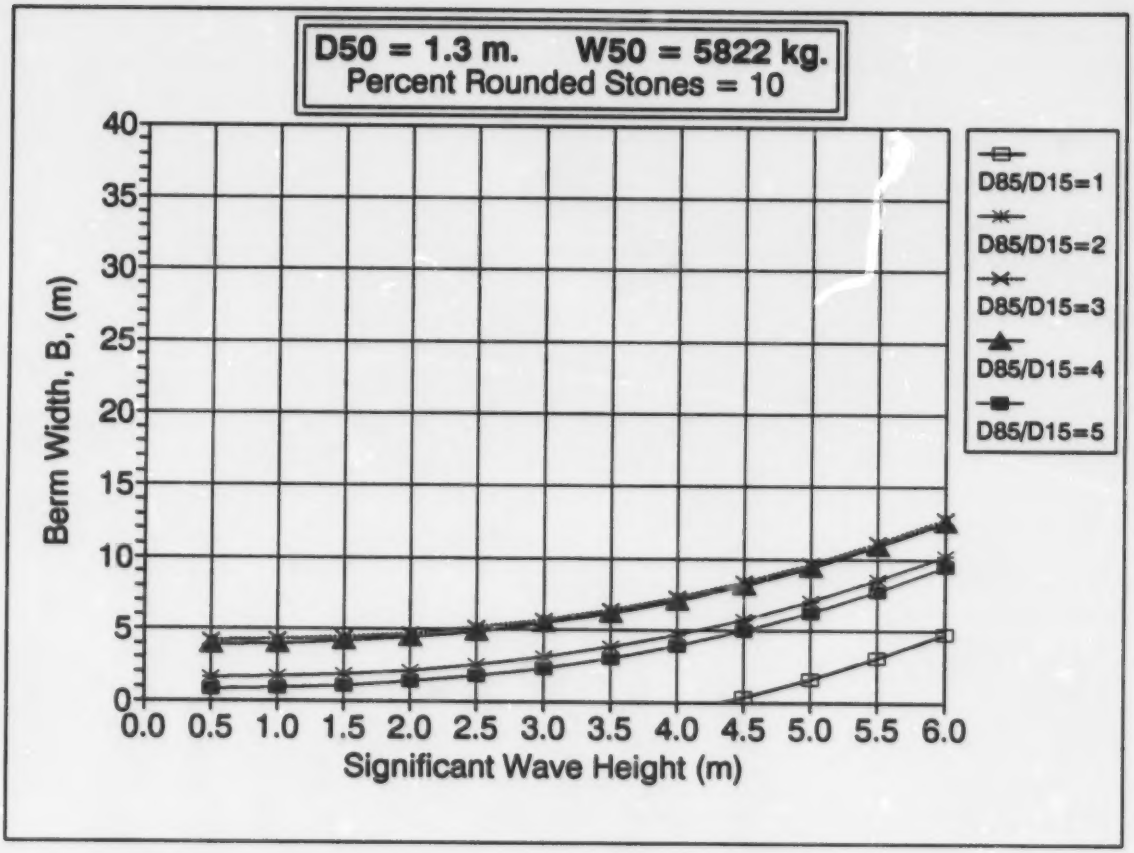

D50 = 0.8 m. W50 = 1357 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

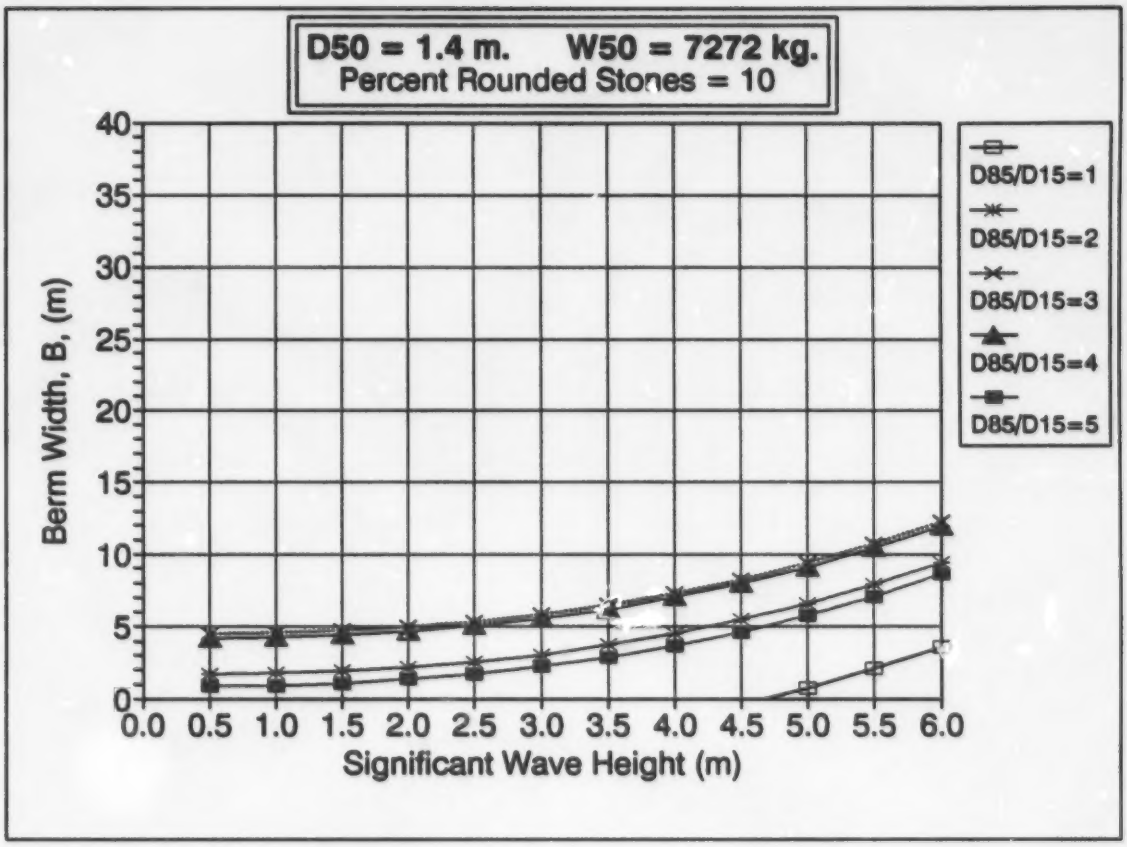

D50 = 0.9 m. W50 = 1932 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

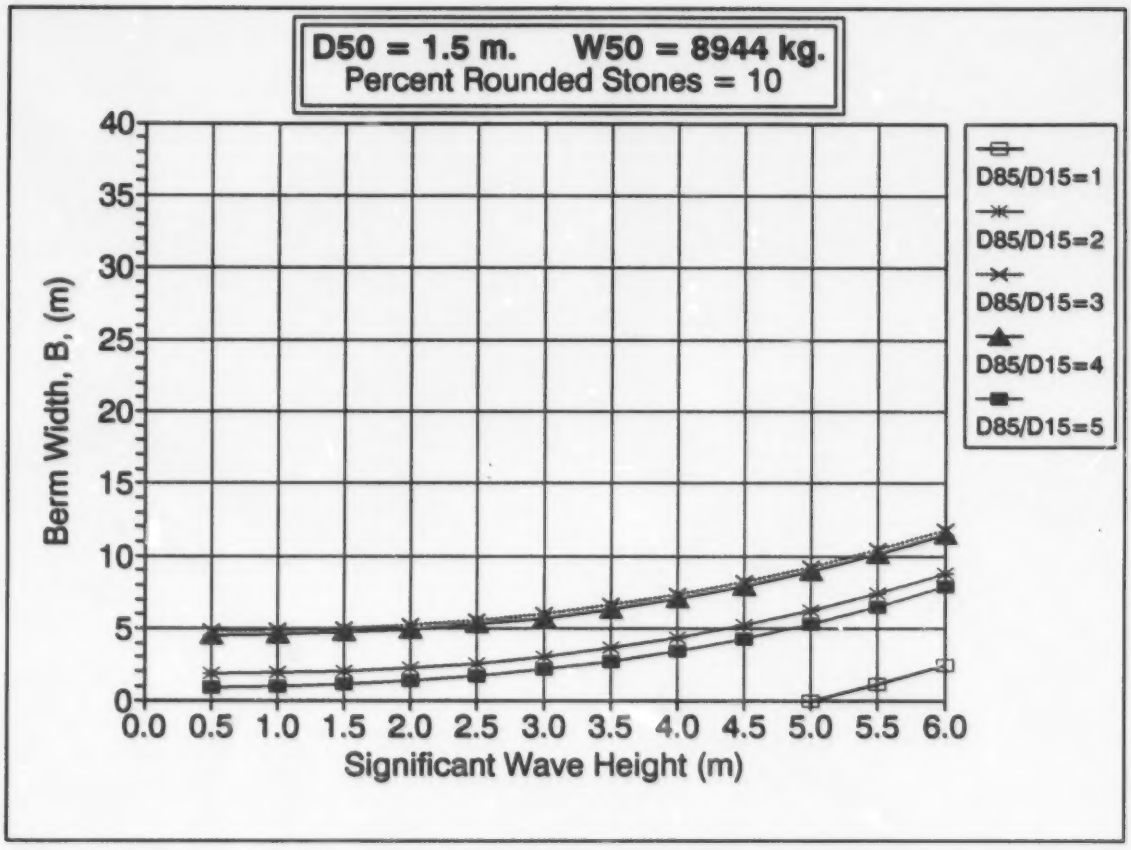

D50 = 1.0 m. W50 = 2650 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

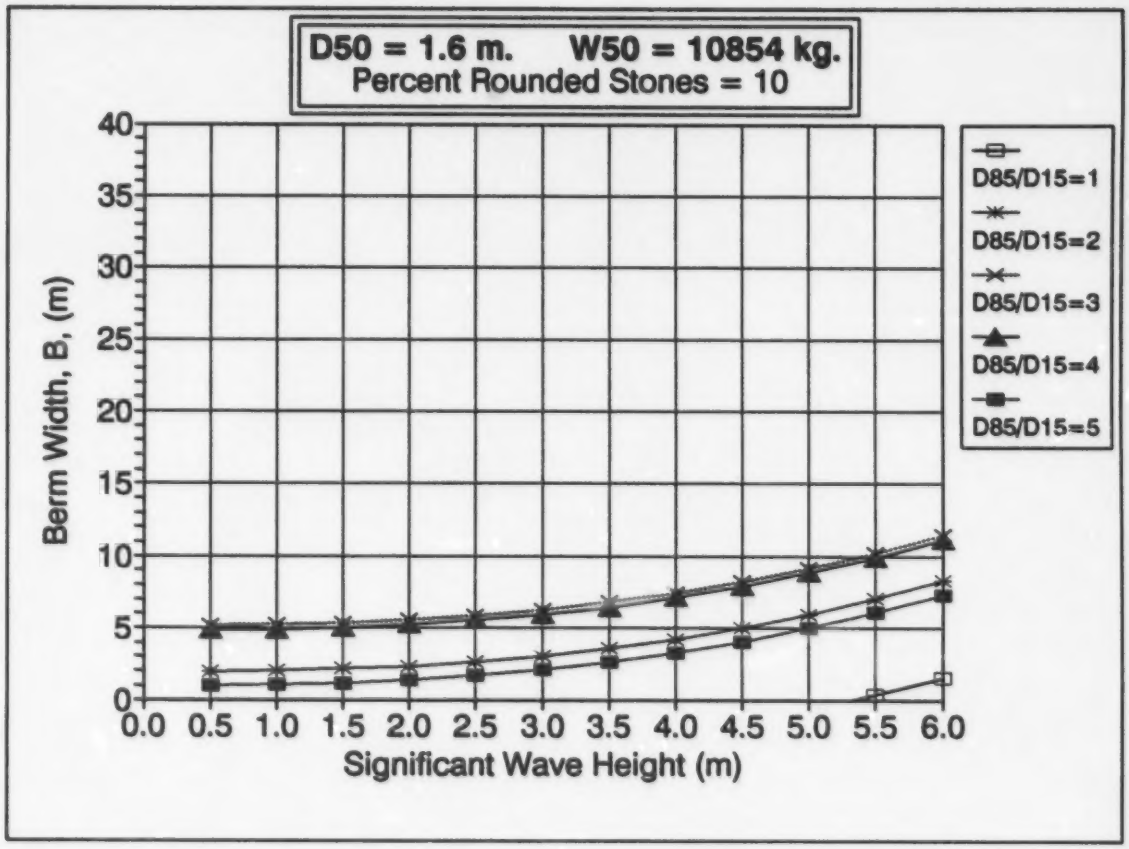

D50 = 1.1 m. W50 = 3527 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

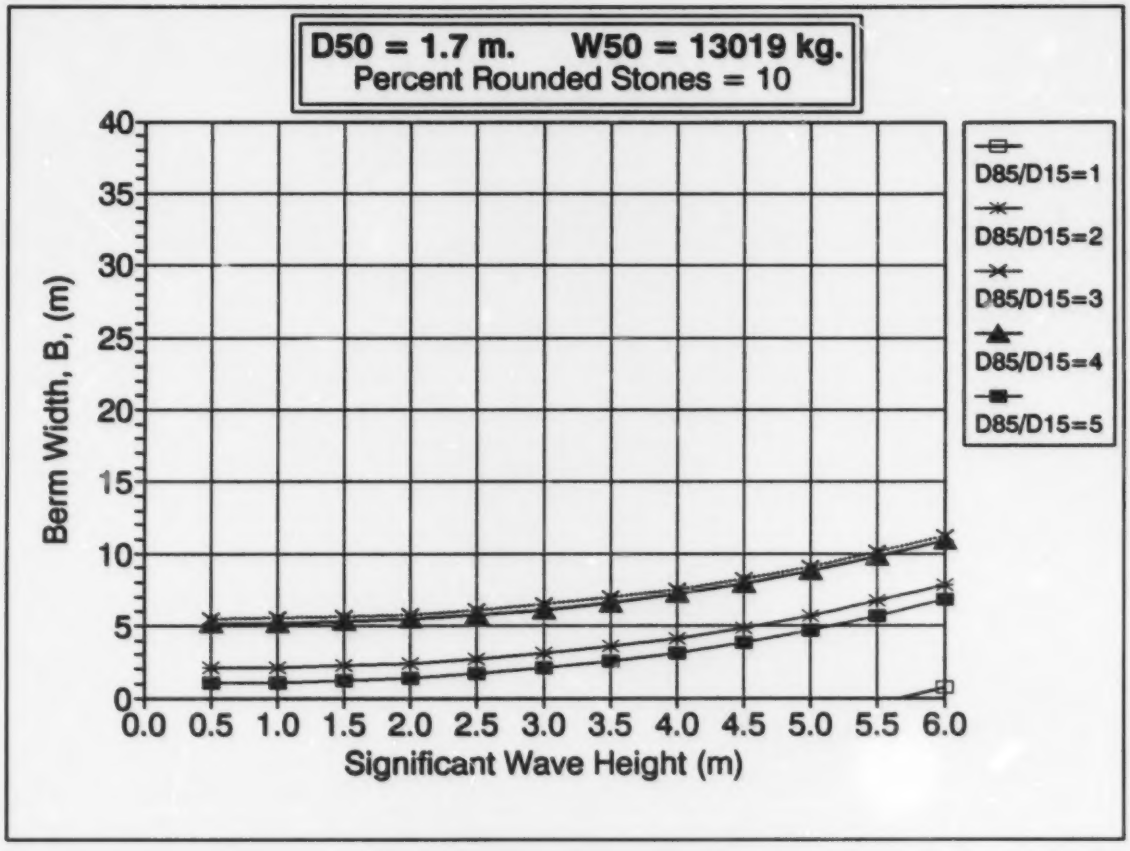

D50 = 1.2 m. W50 = 4579 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

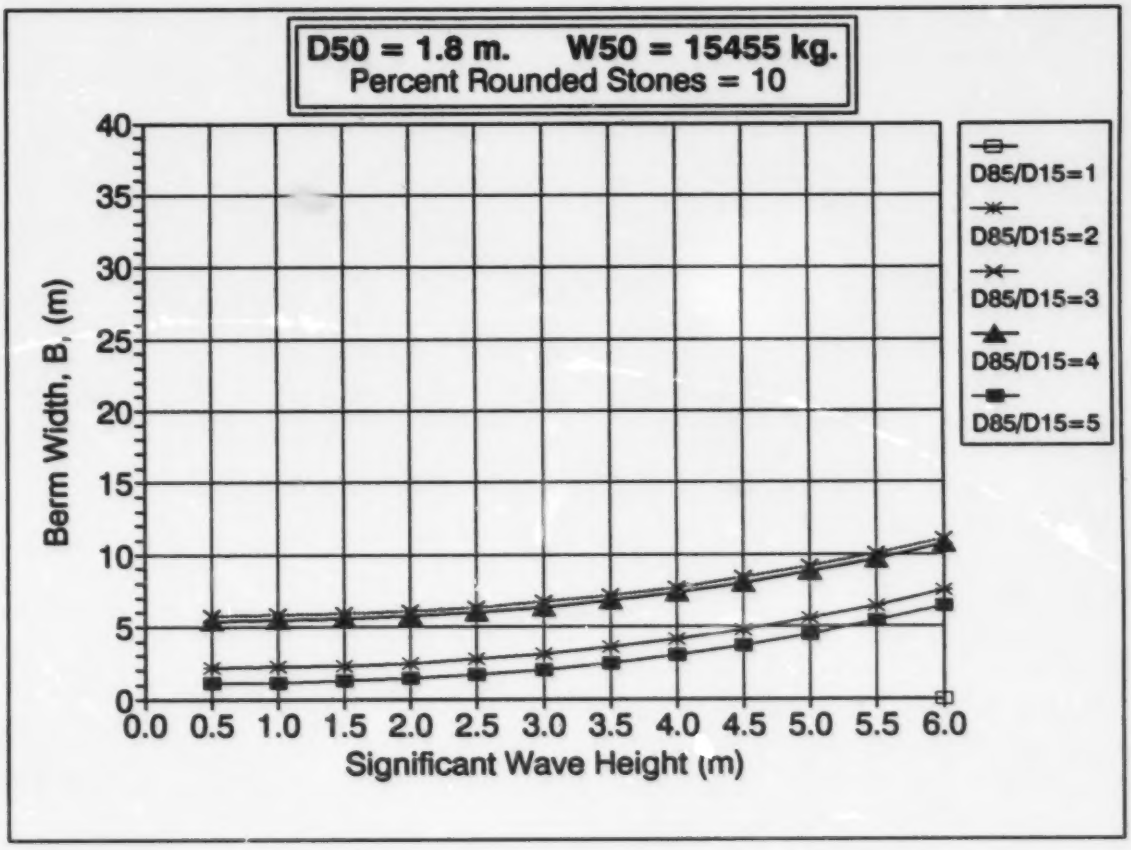

D50 = 1.3 m. W50 = 5822 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

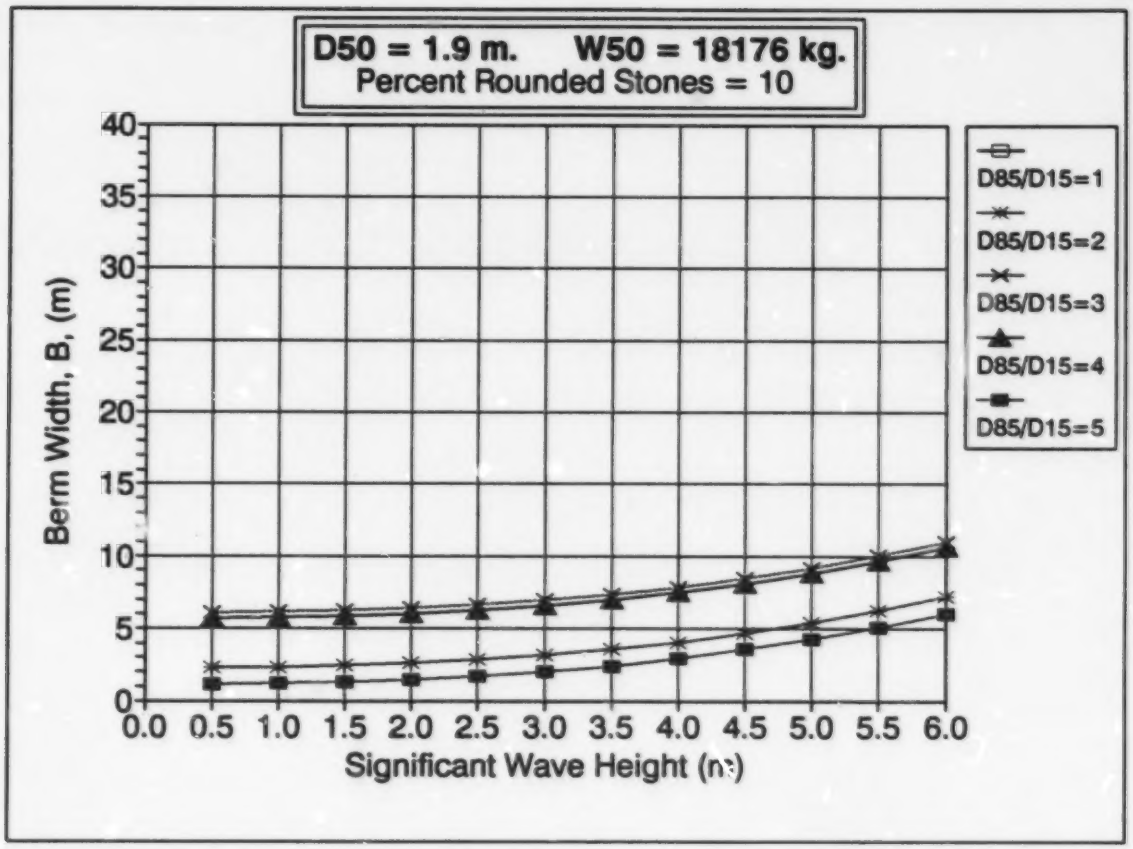

D50 = 1.4 m. W50 = 7272 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

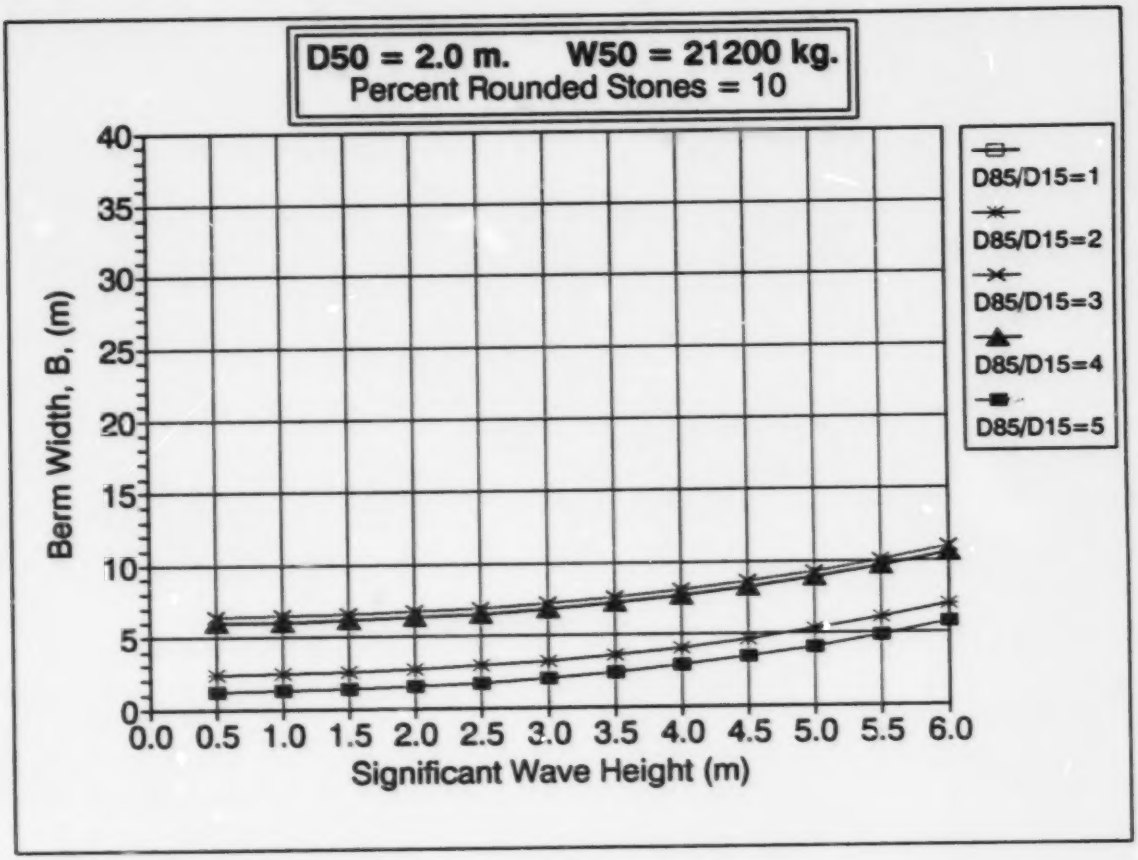

D50 = 1.5 m. W50 = 8944 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

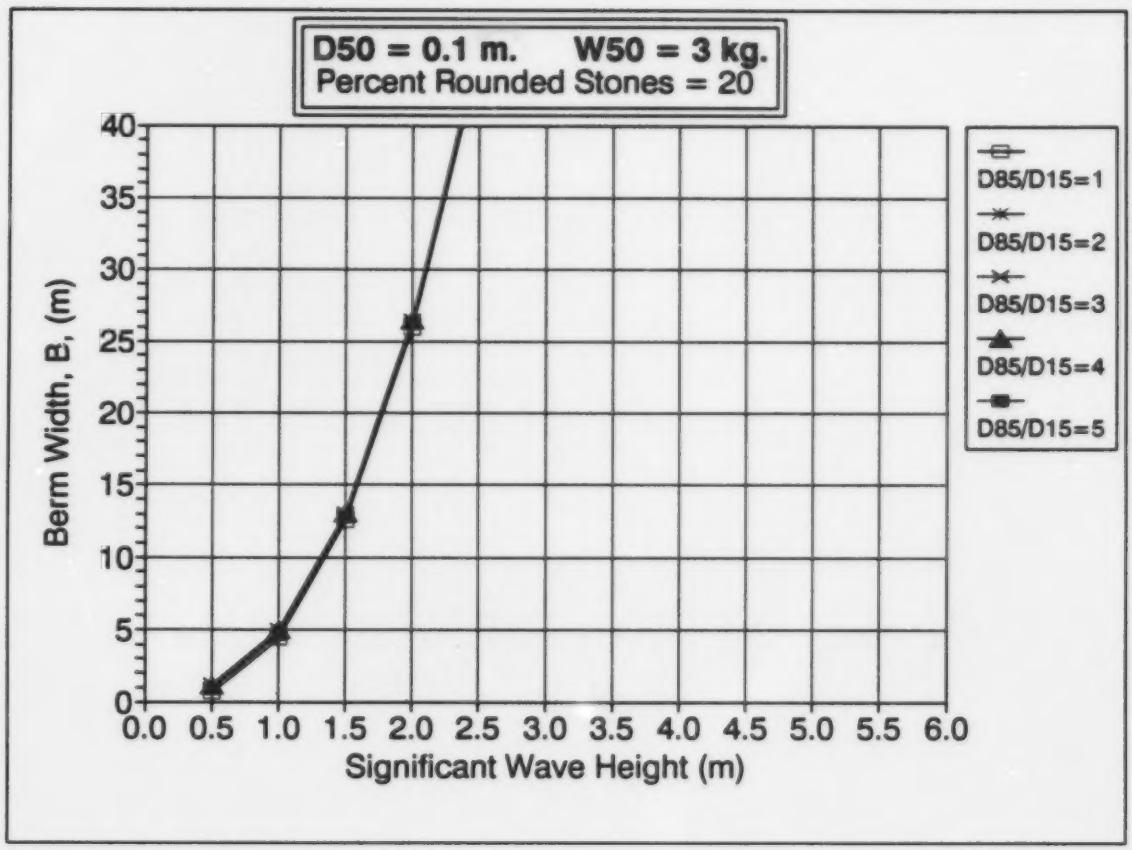

D50 = 1.6 m. W50 = 10854 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

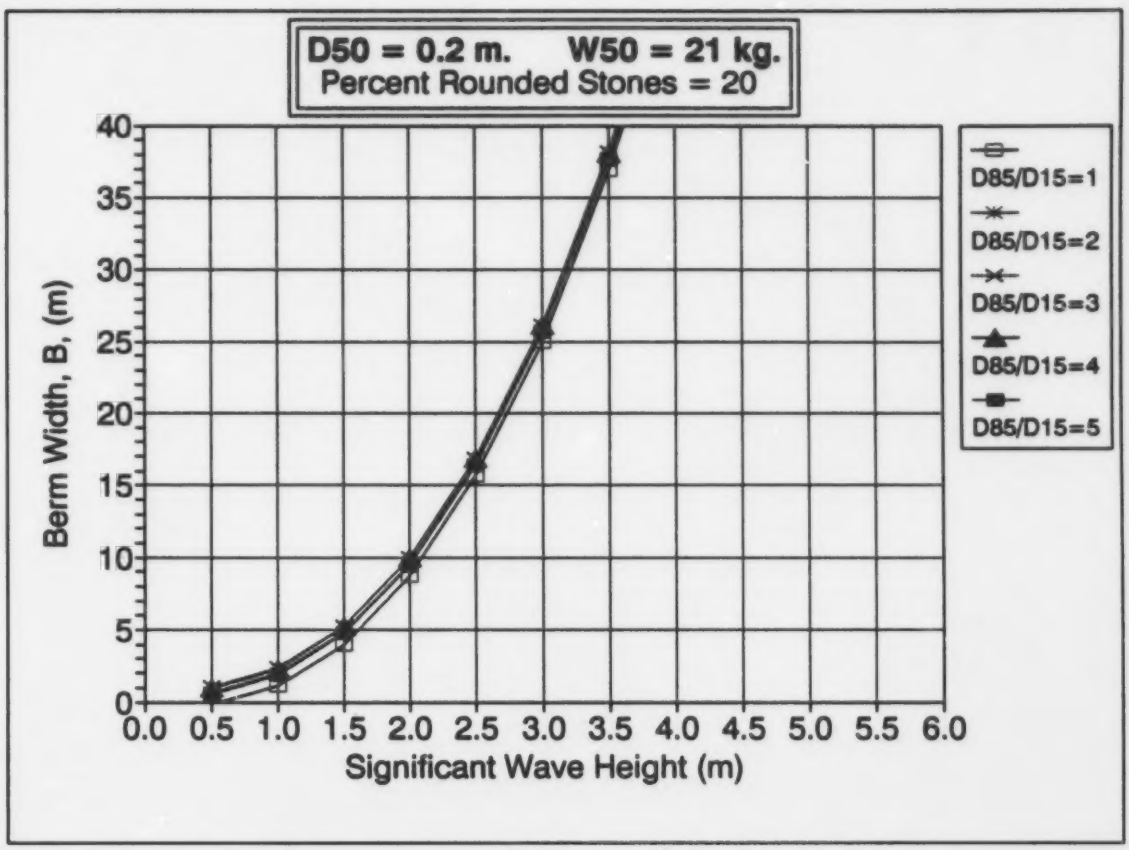

D50 = 1.7 m. W50 = 13019 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

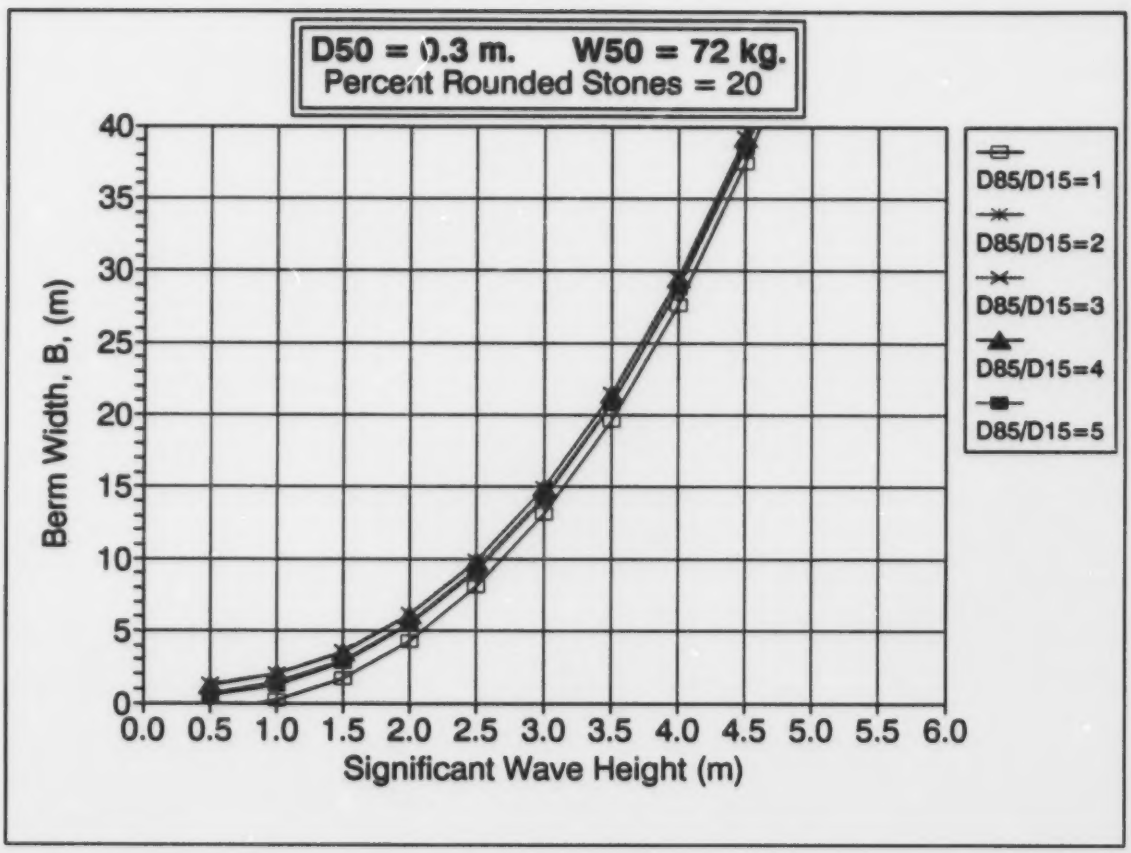

D50 = 1.8 m. W50 = 15455 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

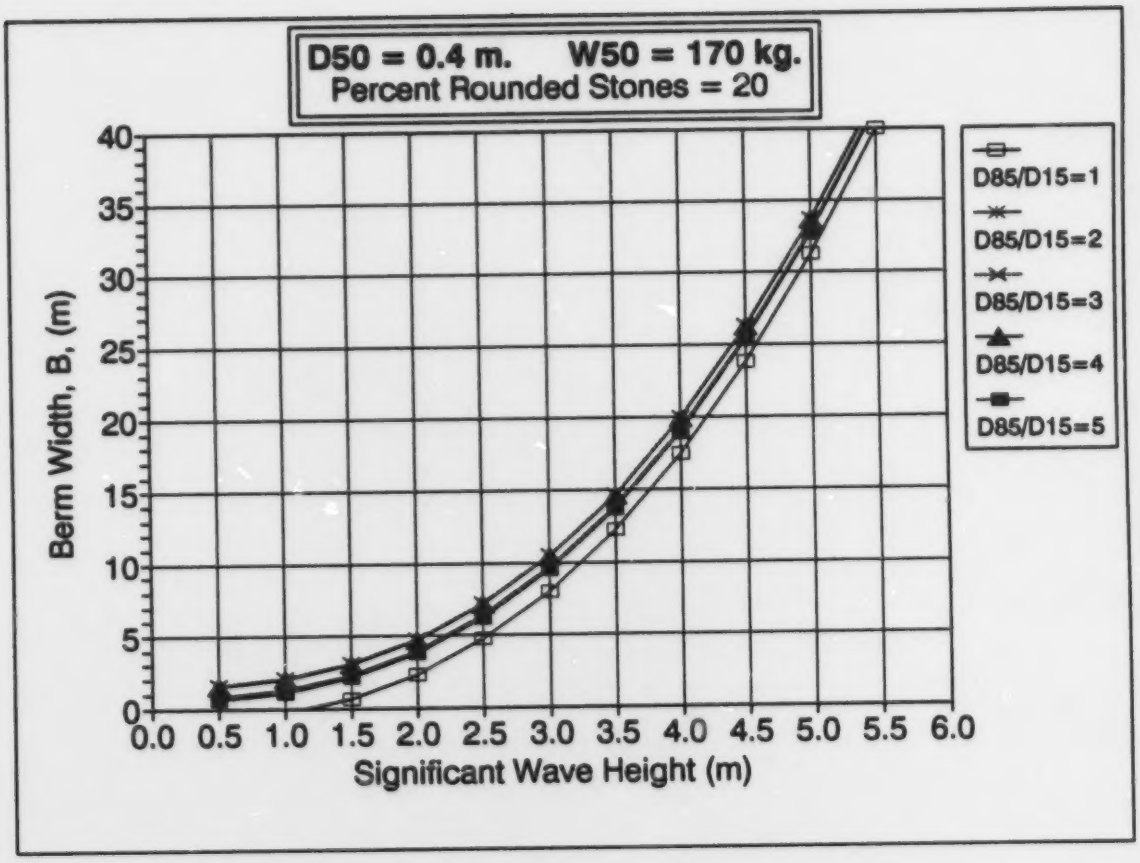

D50 = 1.9 m. W50 = 18176 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

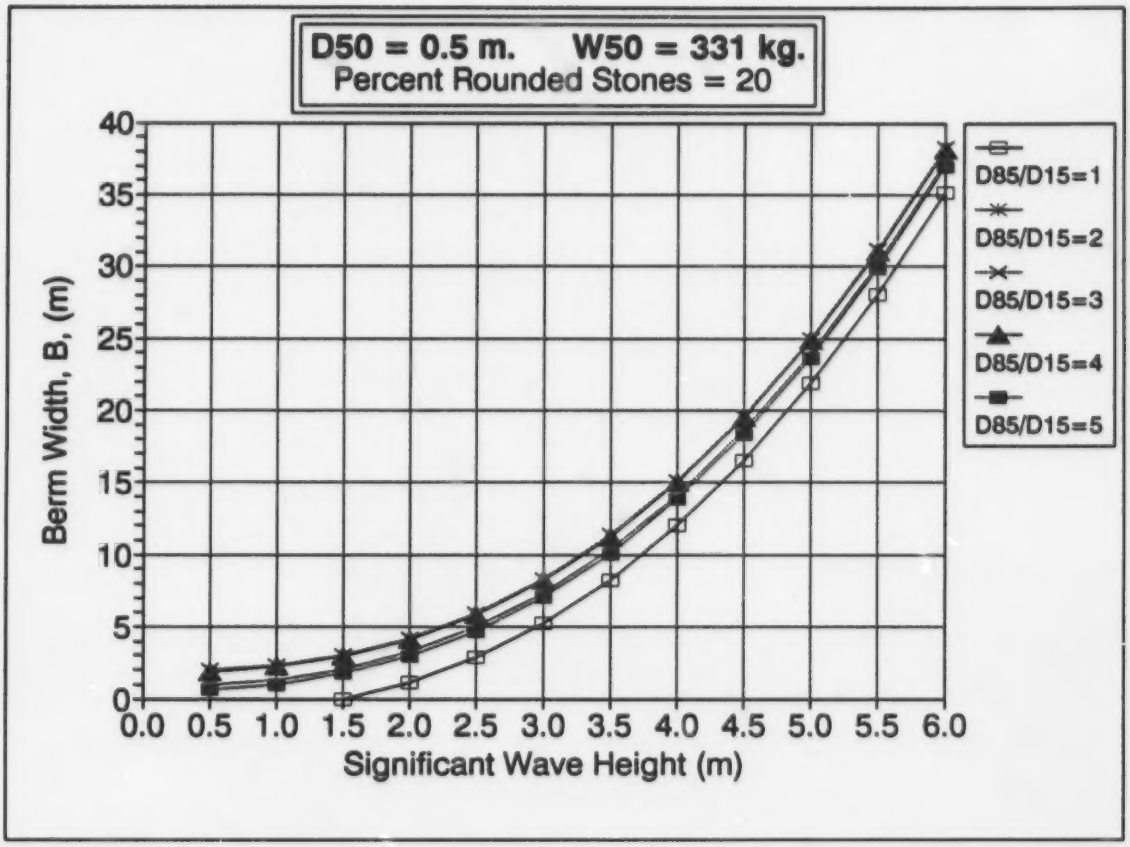

D50 = 2.0 m. W50 = 21200 kg.
Percent Rounded Stones = 10
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

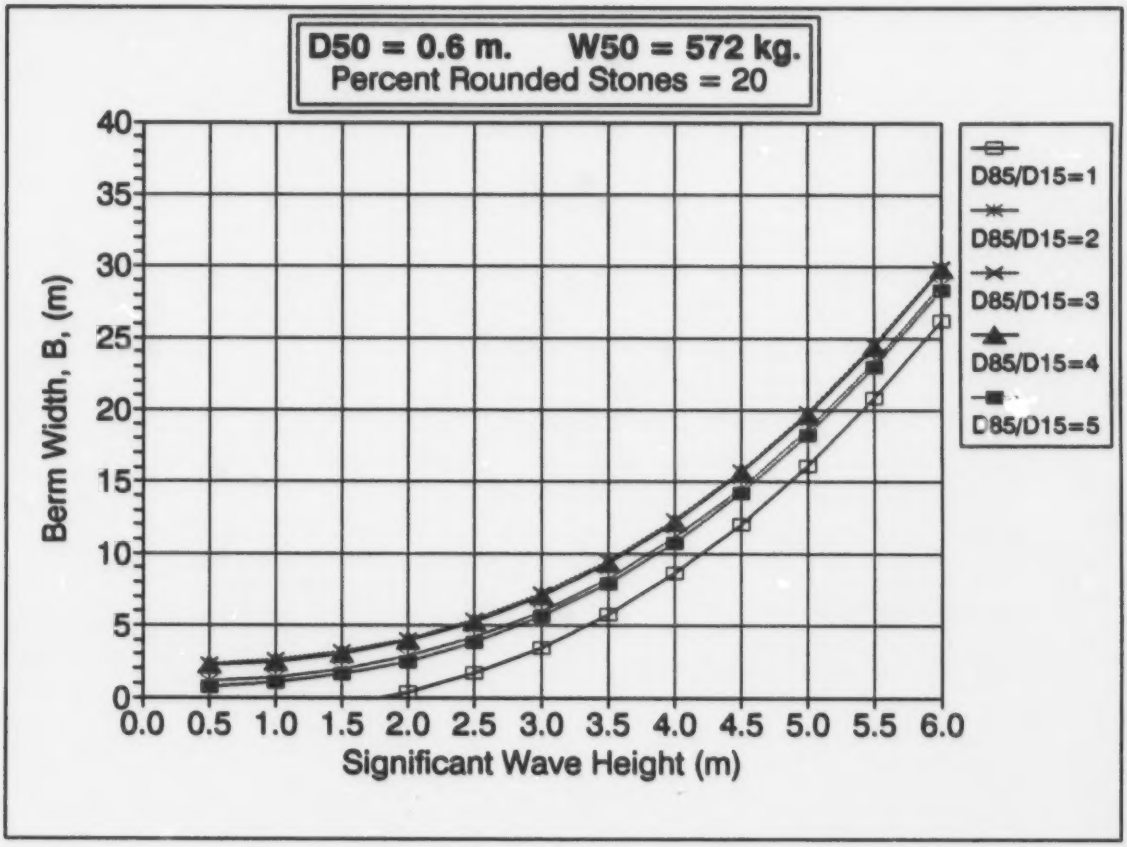

D50 = 0.1 m. W50 = 3 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

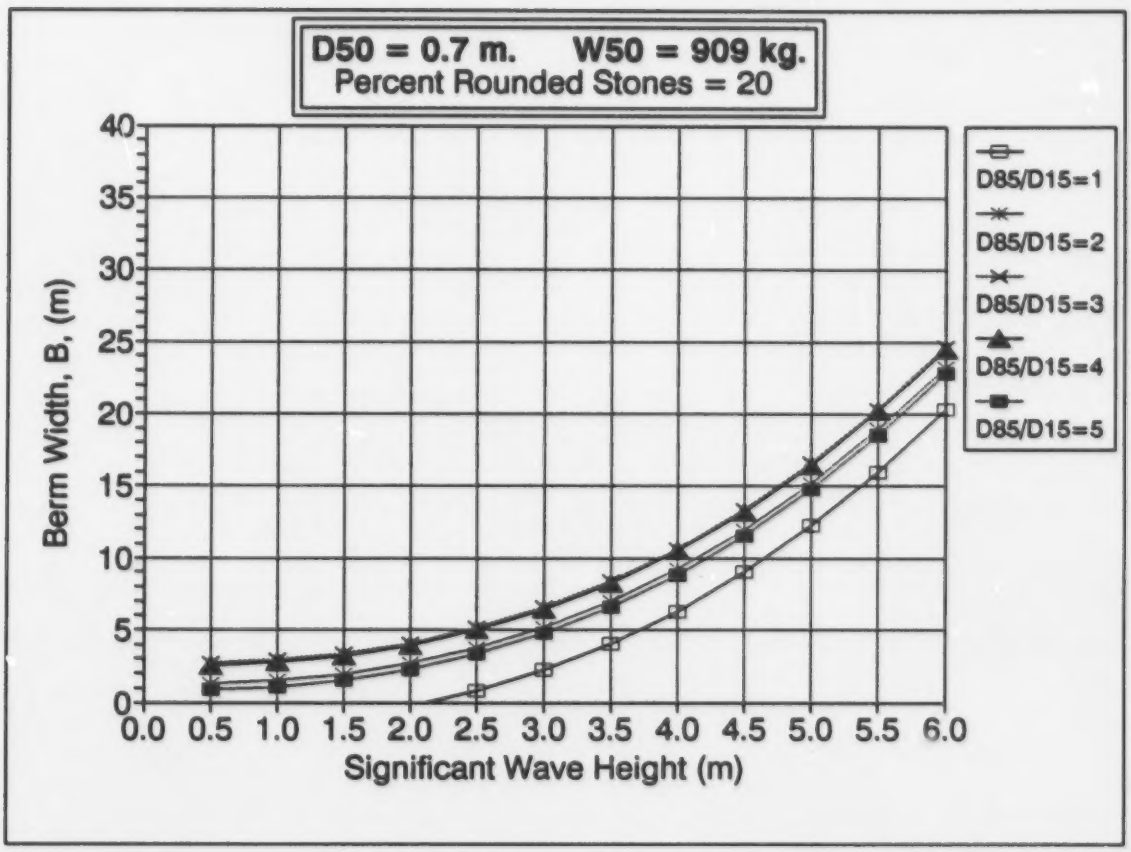

D50 = 0.2 m. W50 = 21 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

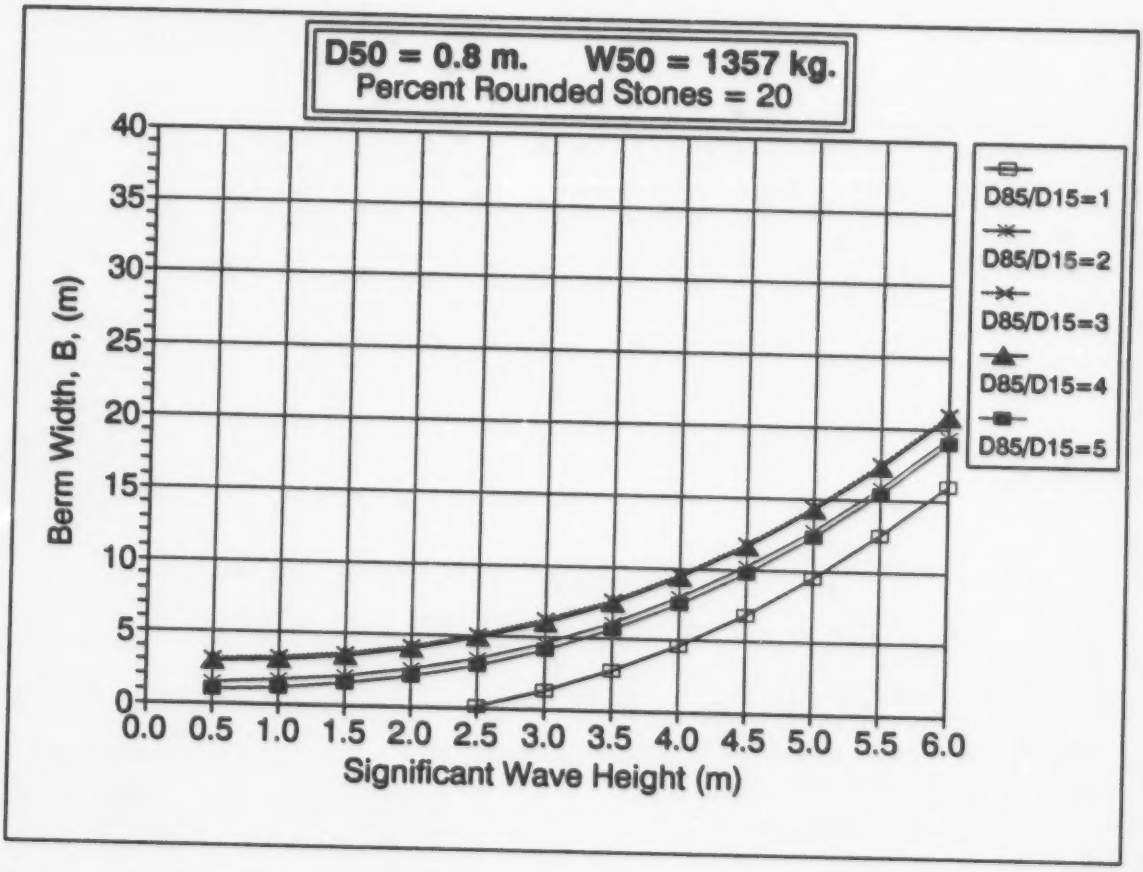

D50 = 0.3 m. W50 = 72 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

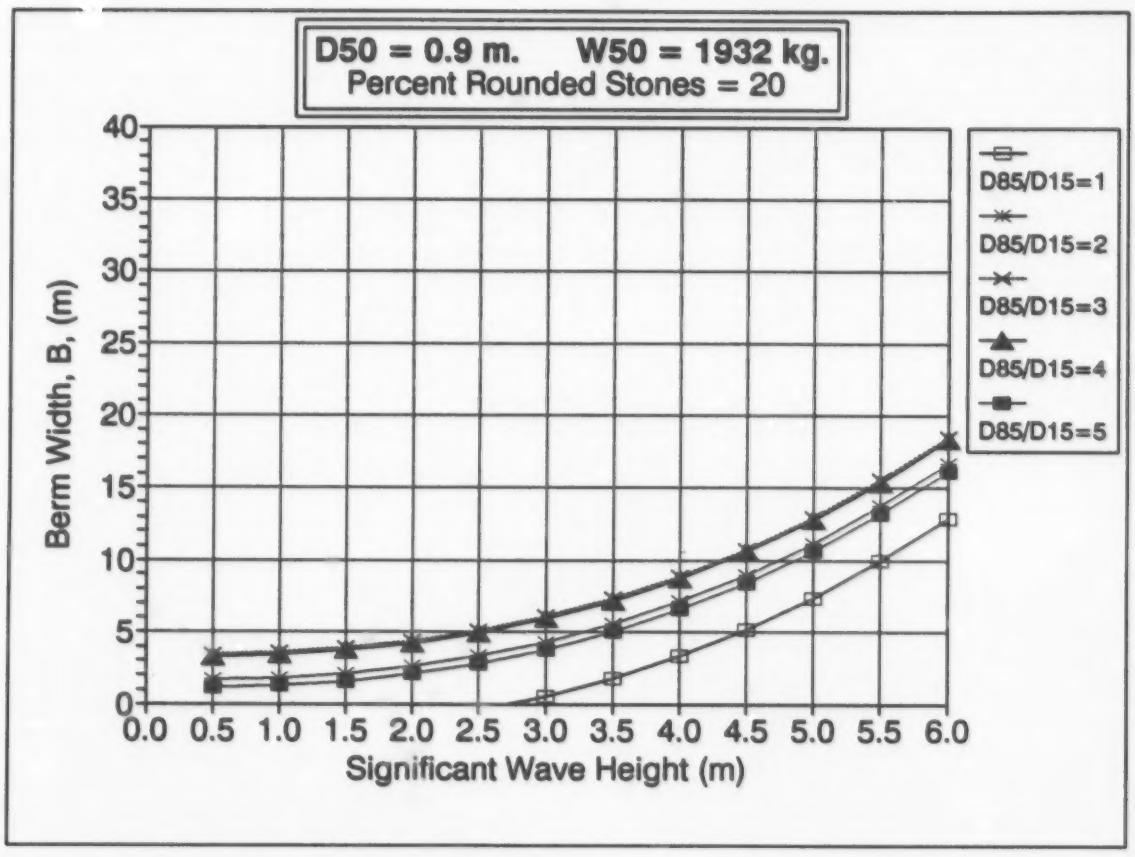

D50 = 0.4 m. W50 = 170 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

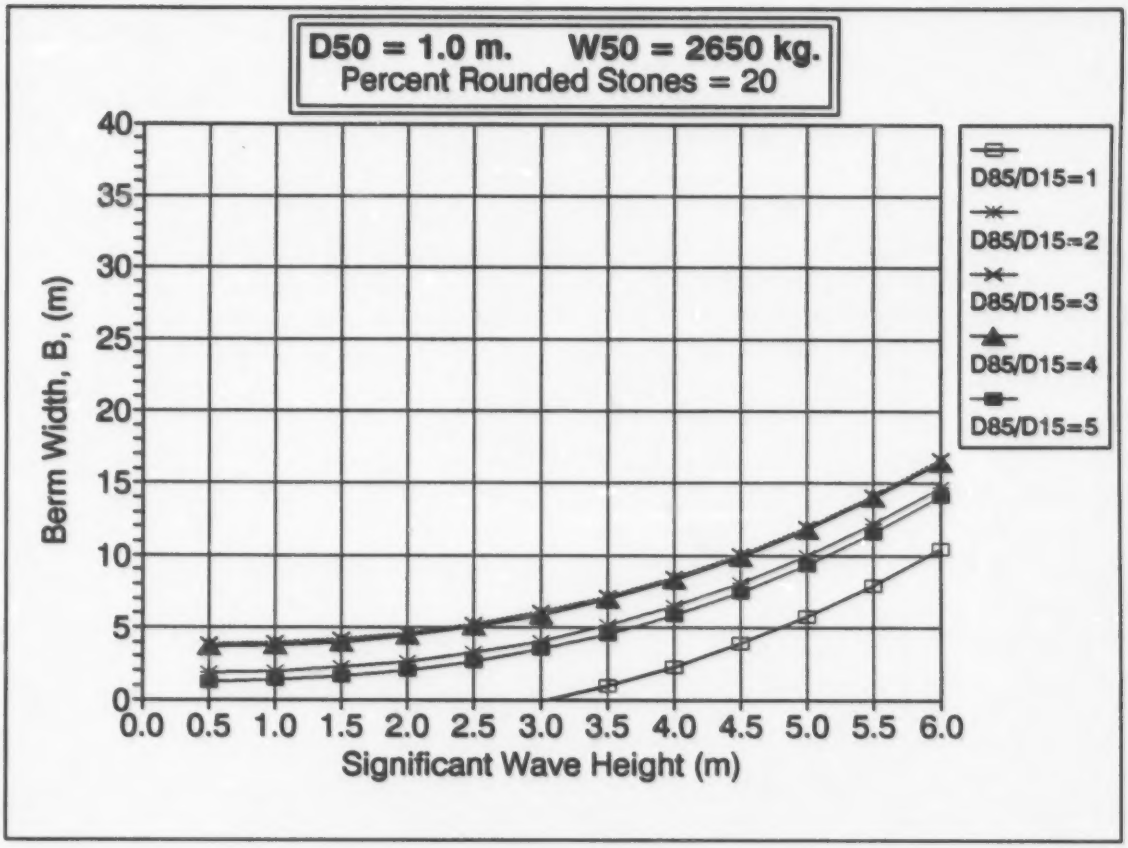

D50 = 0.5 m. W50 = 331 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

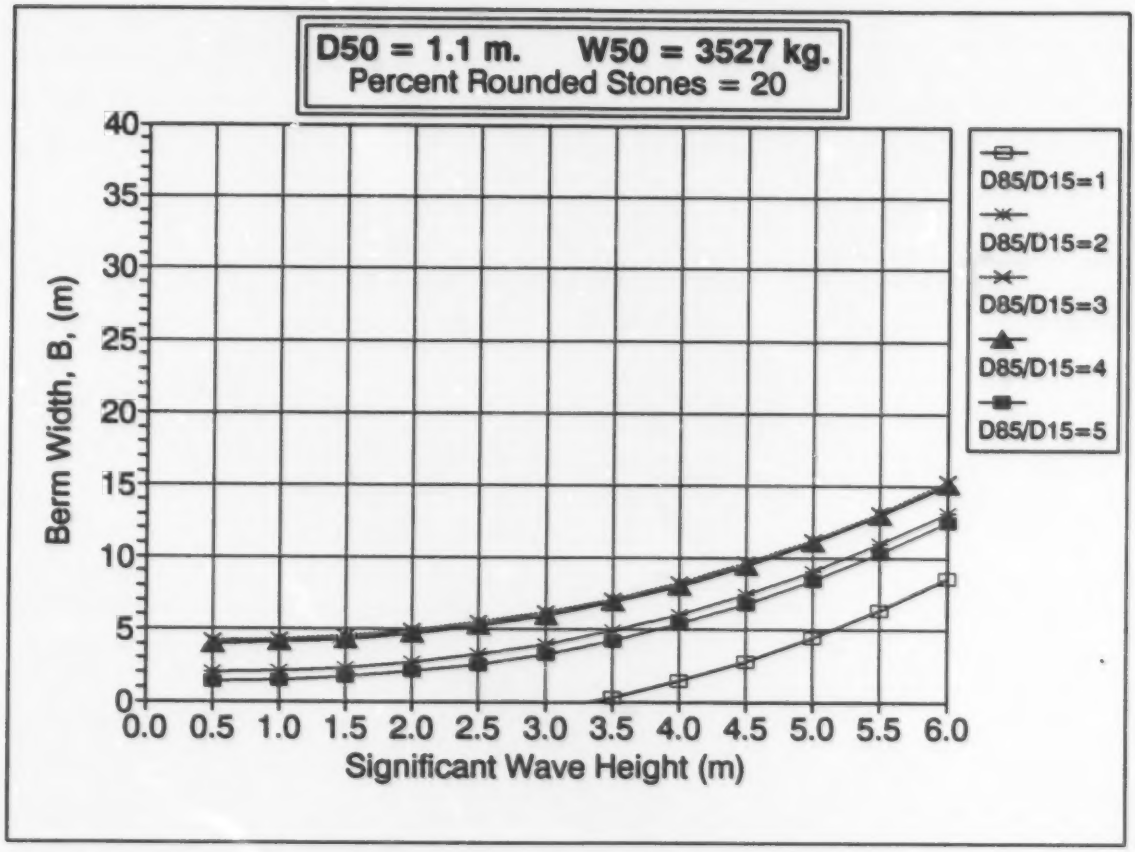

D50 = 0.6 m. W50 = 572 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

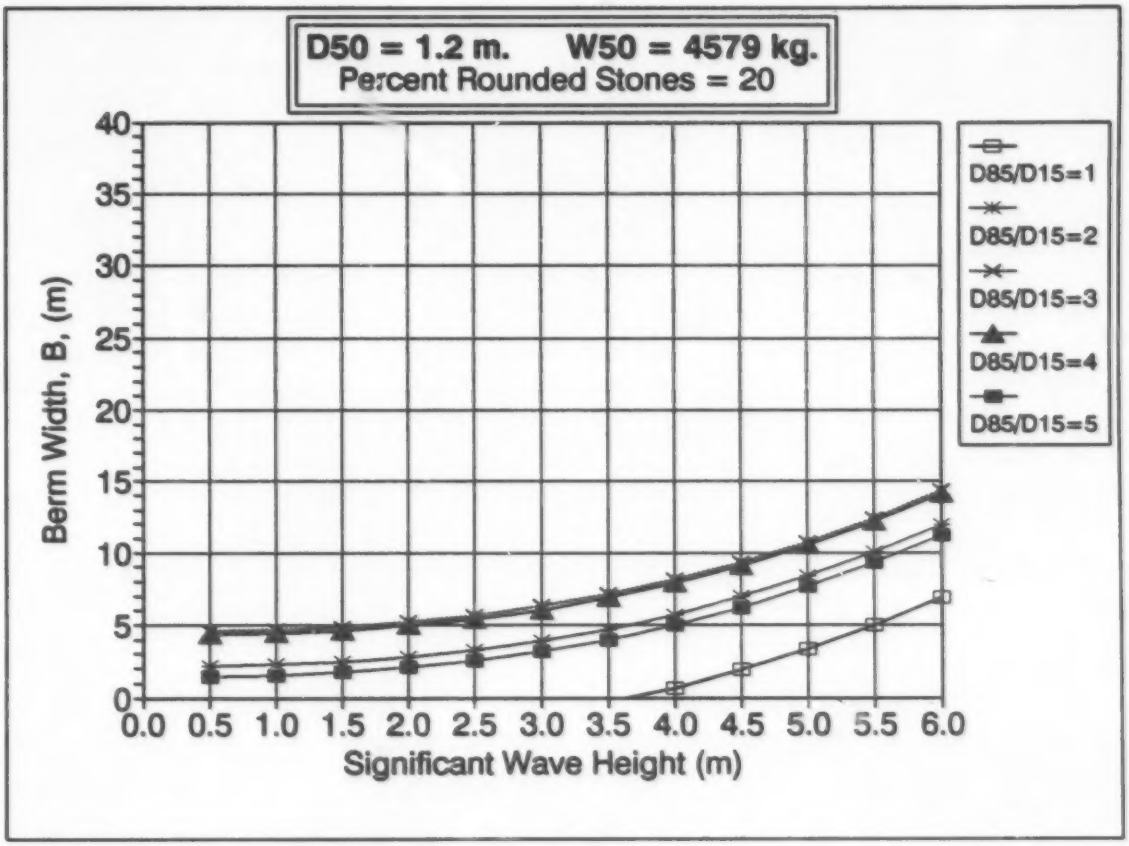

D50 = 0.7 m. W50 = 909 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

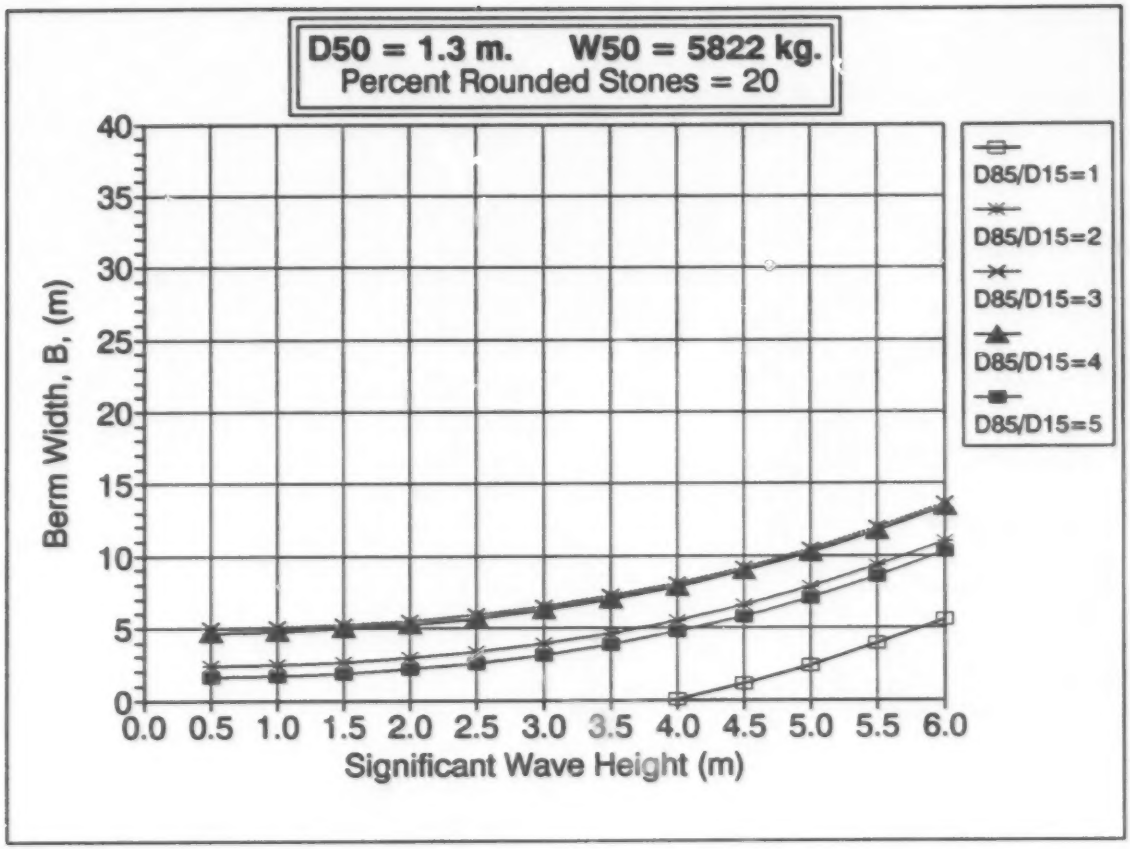

D50 = 0.8 m. W50 = 1357 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

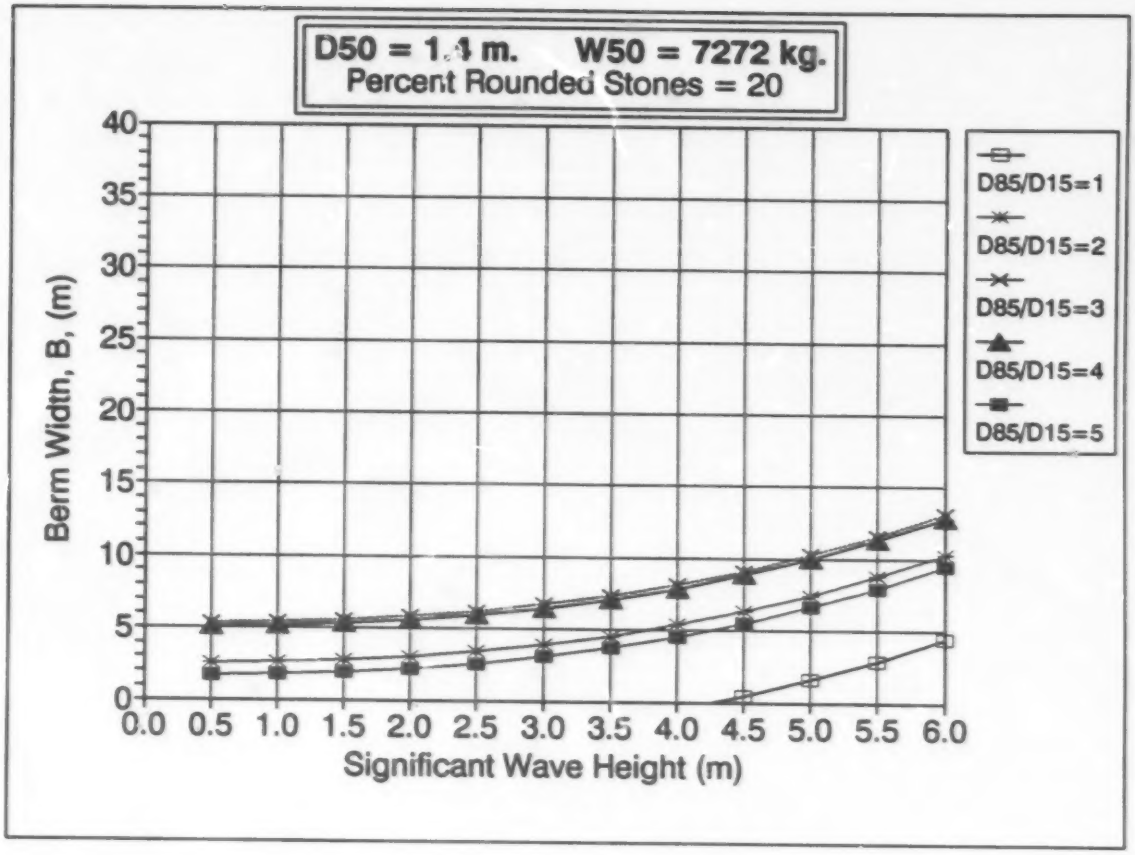

D50 = 0.9 m. W50 = 1932 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

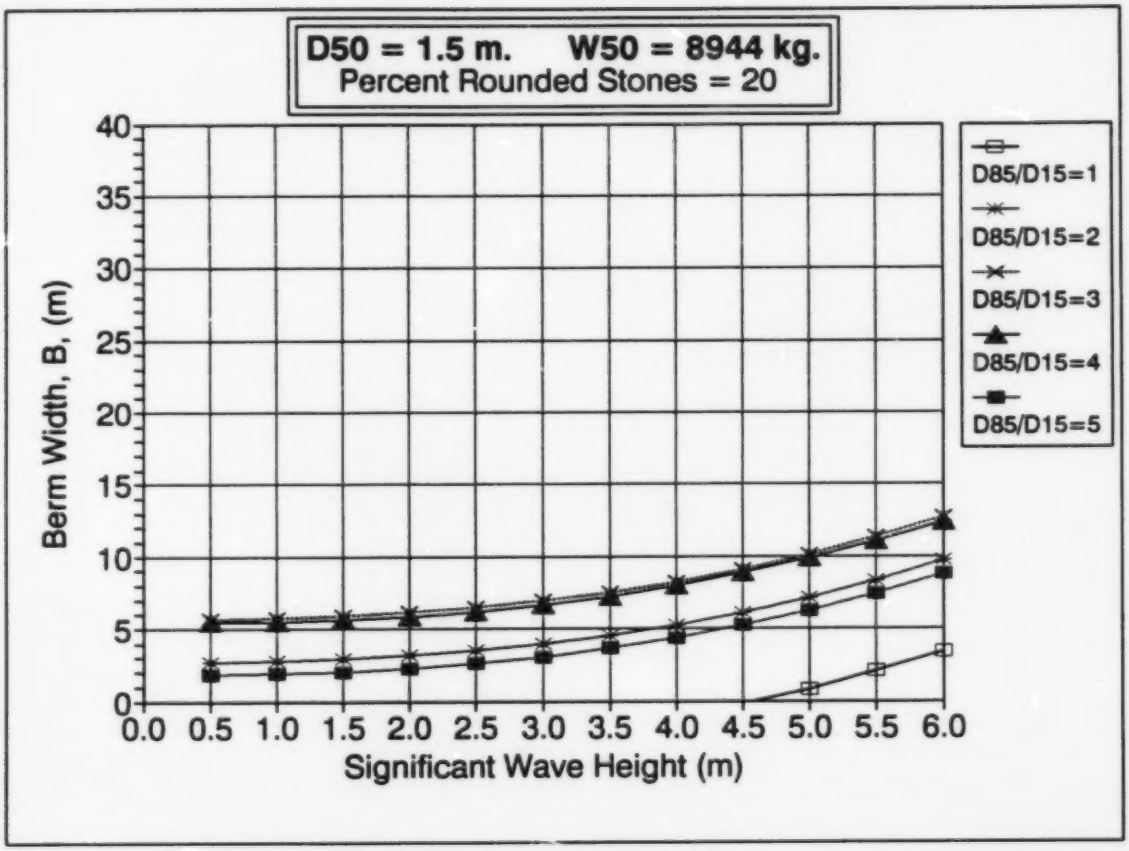

D50 = 1.0 m. W50 = 2650 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

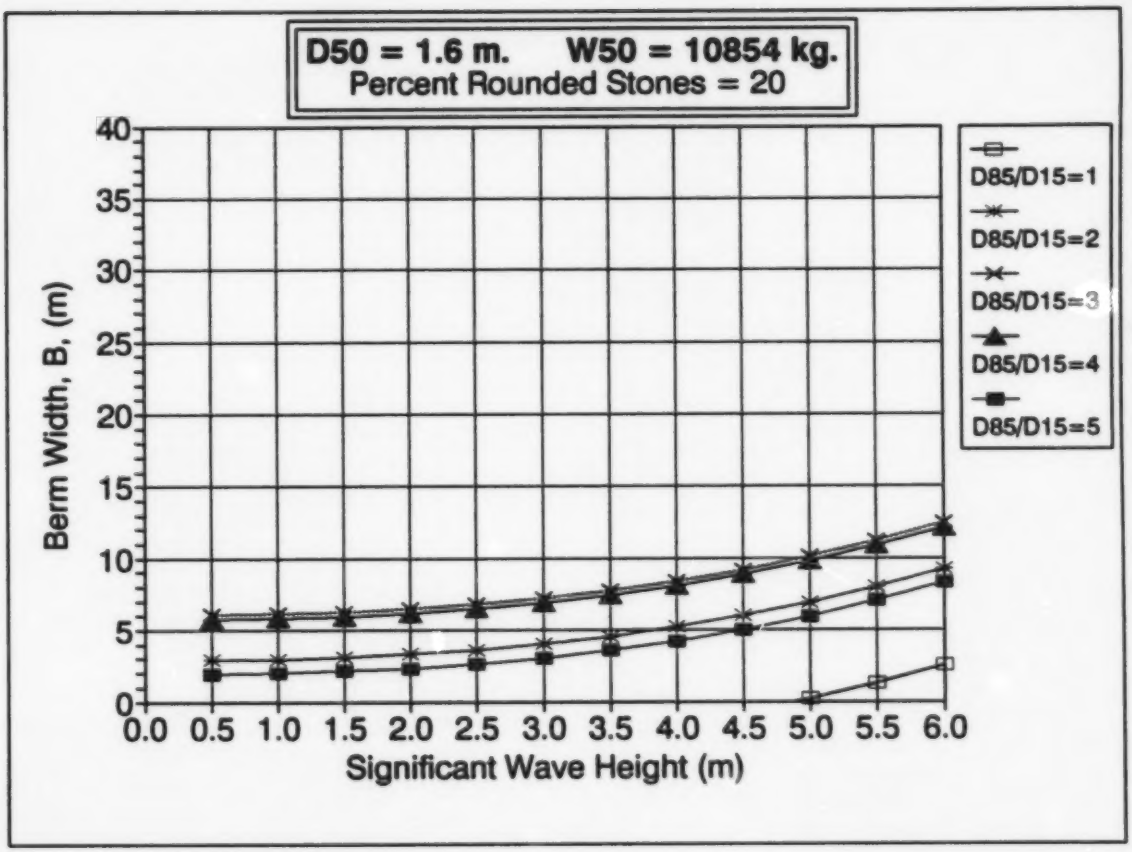

D50 = 1.1 m. W50 = 3527 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

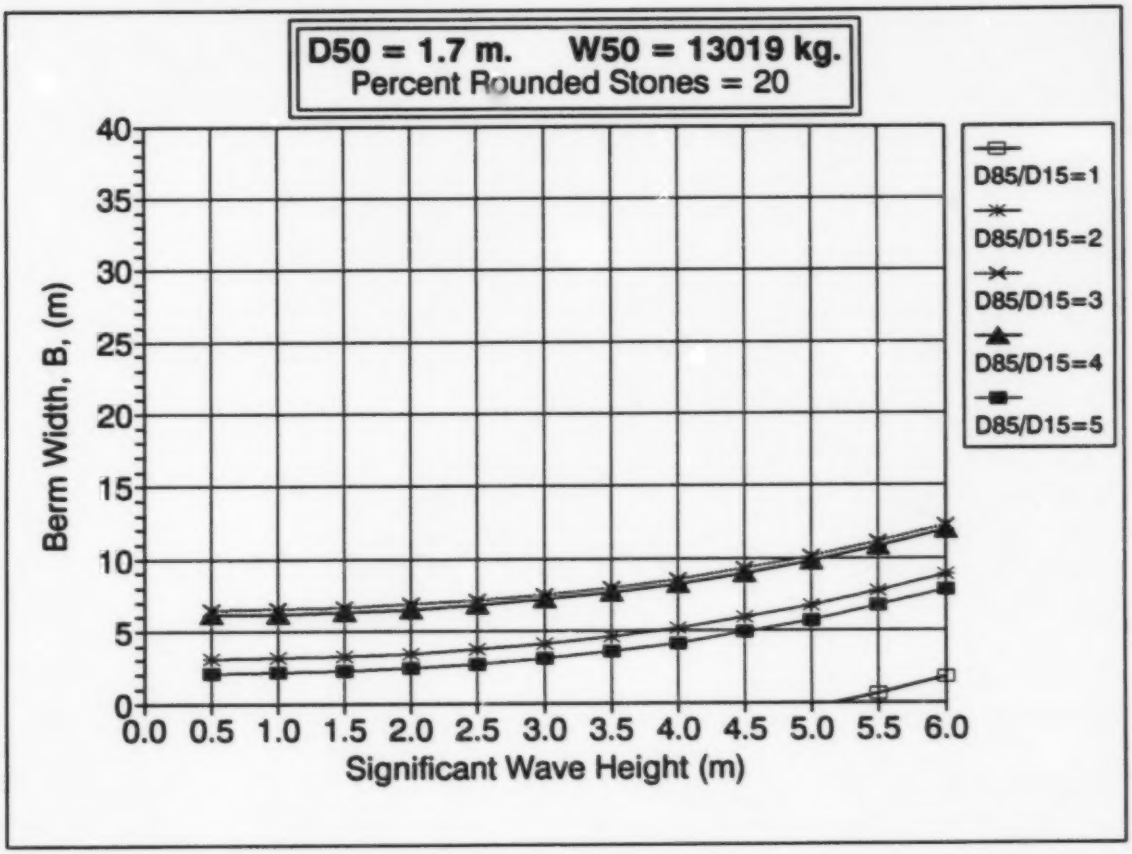

D50 = 1.2 m. W50 = 4579 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

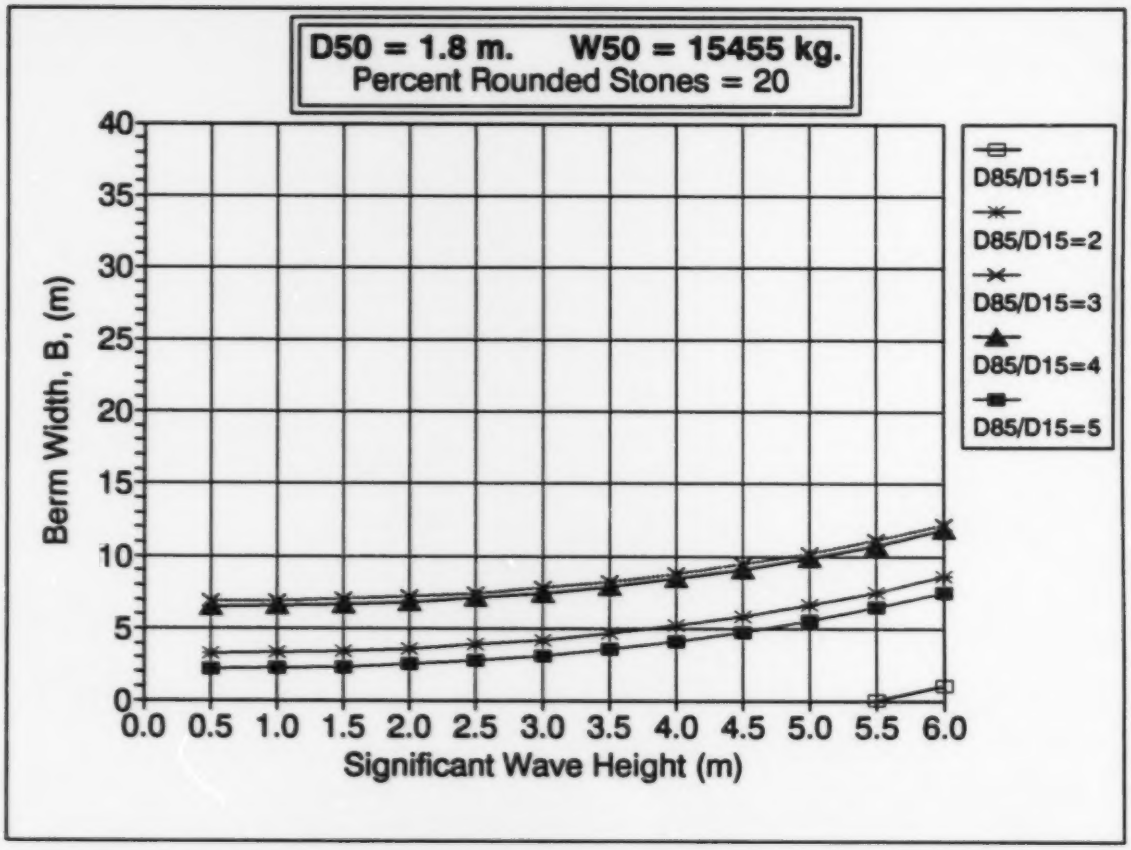

D50 = 1.3 m. W50 = 5822 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
40
35
30
25
20
15
10
5
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

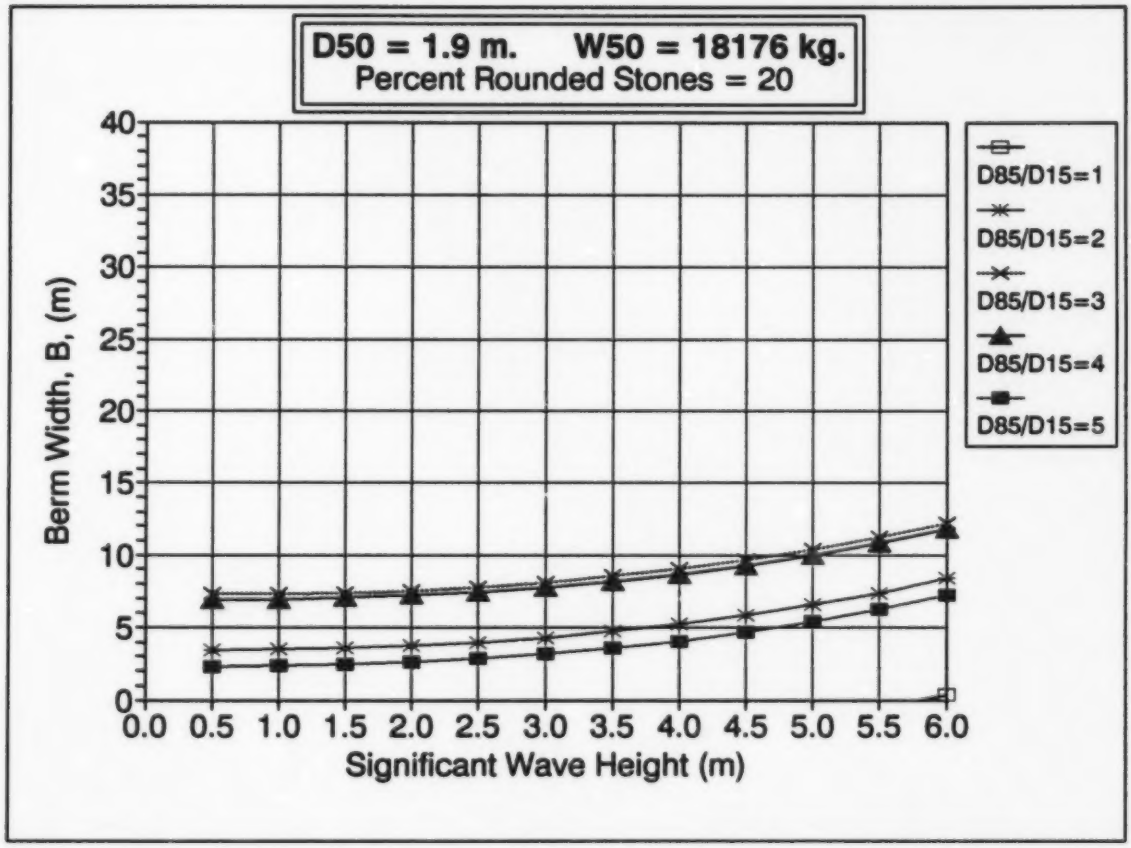

D50 = 1.4 m. W50 = 7272 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

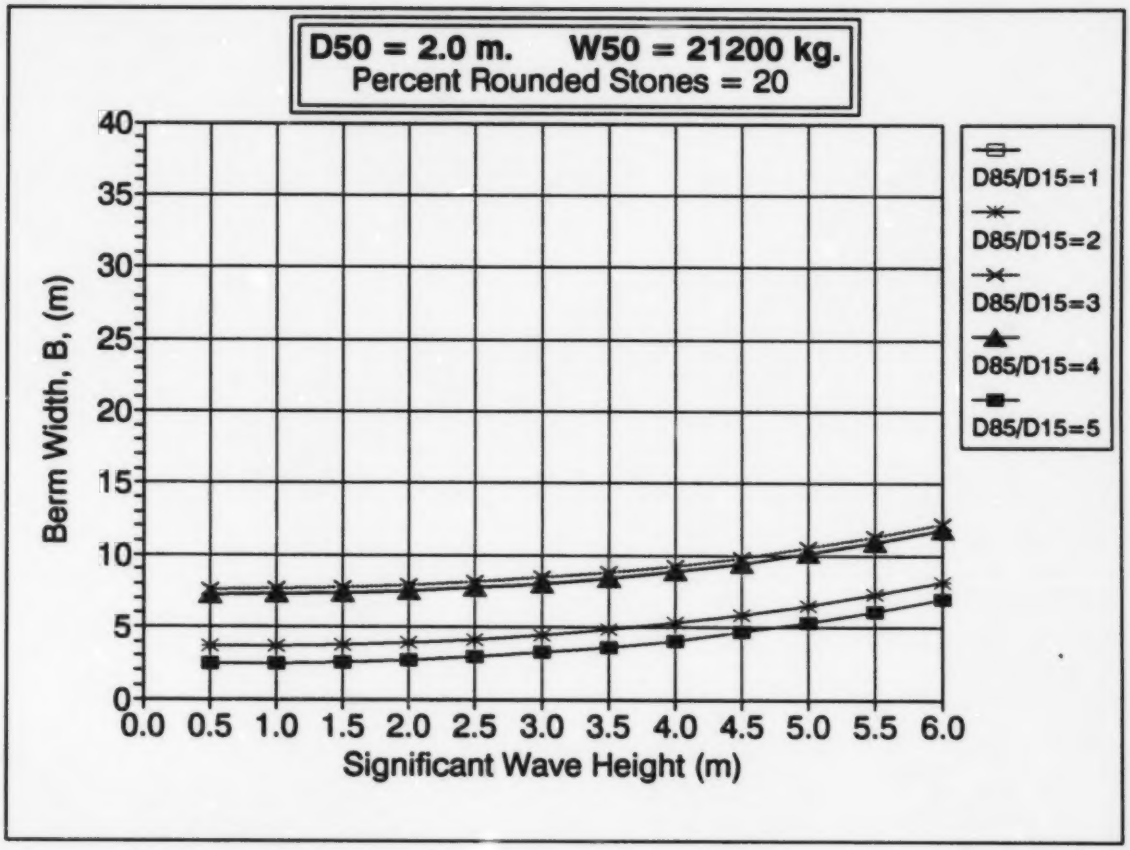

D50 = 1.5 m. W50 = 8944 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

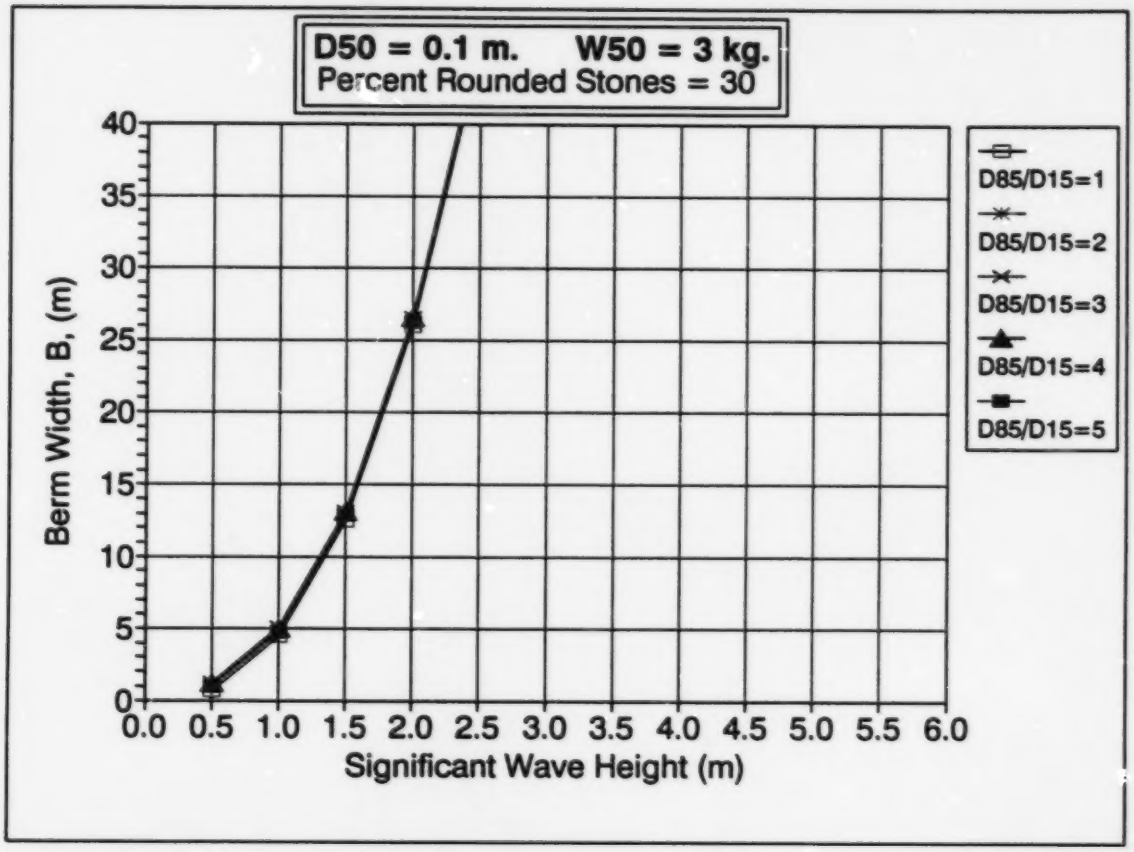

D50 = 1.6 m. W50 = 10854 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

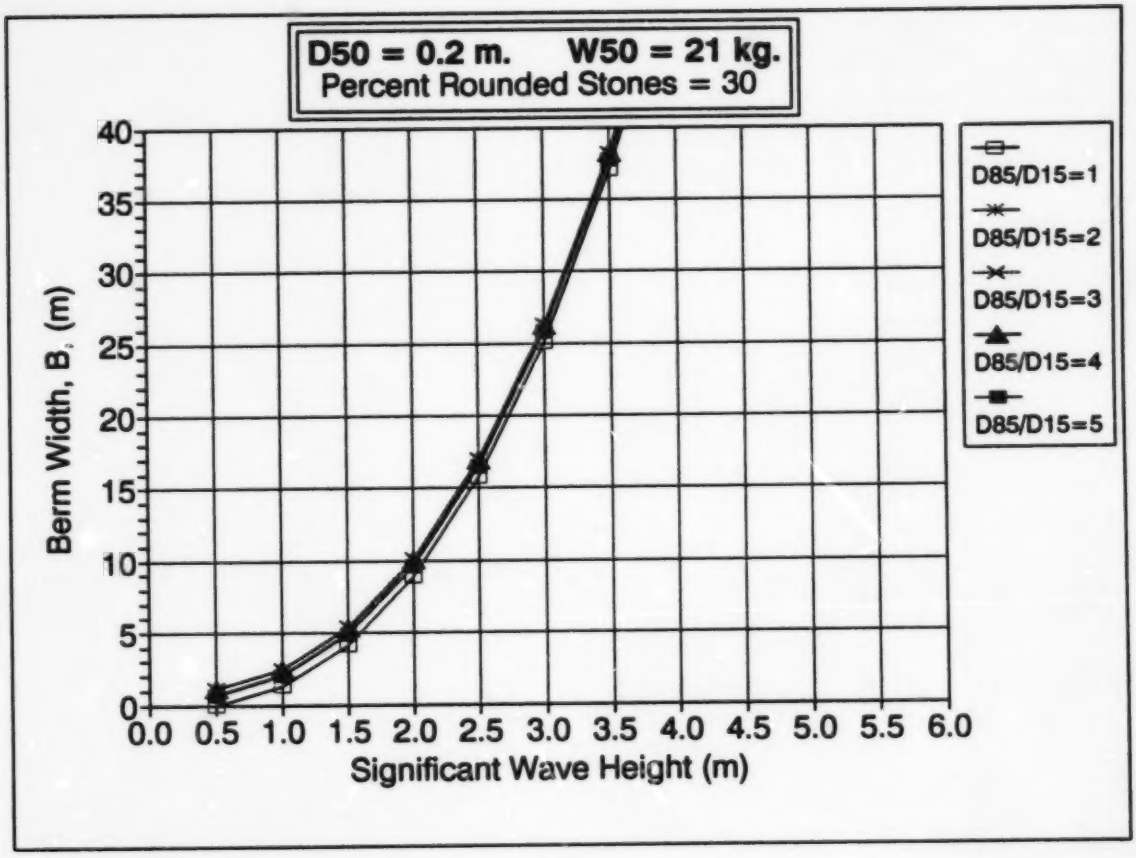

D50 = 1.7 m. W50 = 13019 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.8 m. W50 = 15455 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.9 m. W50 = 18176 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 2.0 m. W50 = 21200 kg.
Percent Rounded Stones = 20
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 0.1 m. W50 = 3 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5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Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
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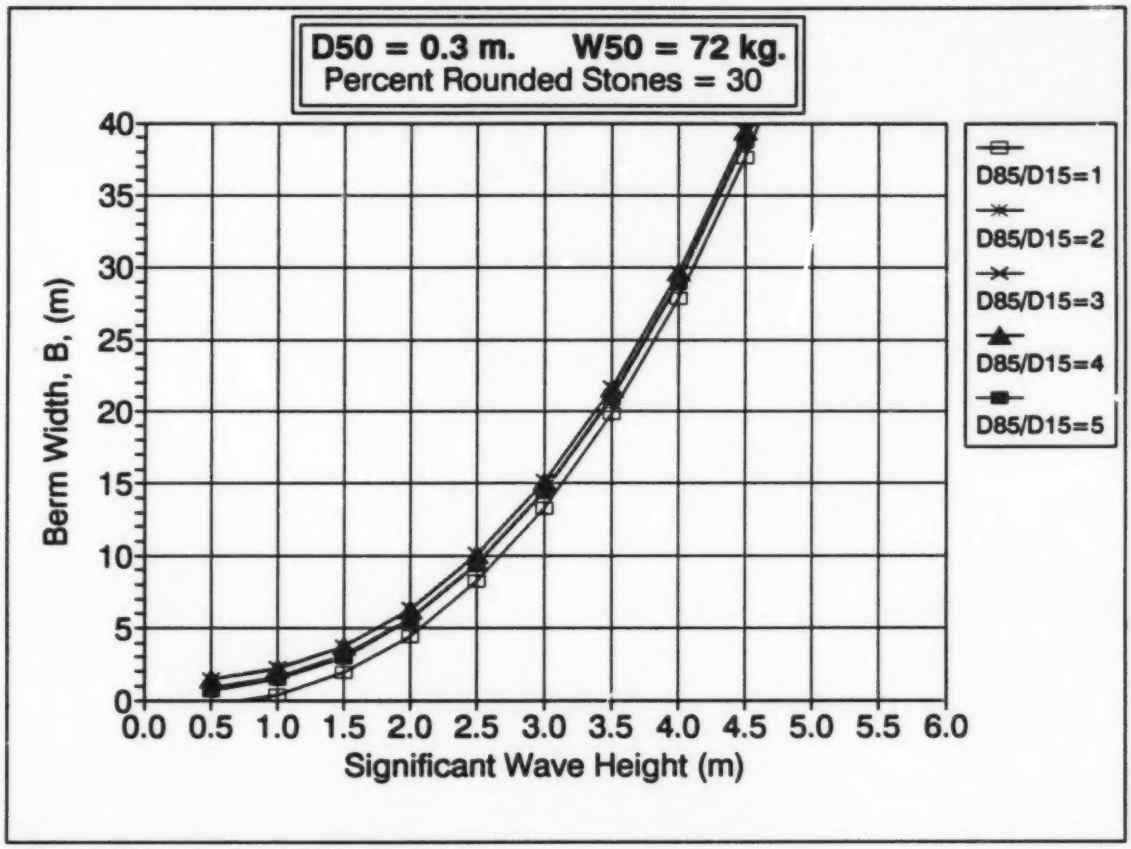
D85/D15=3
D85/D15=4
D85/D15=5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Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
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5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
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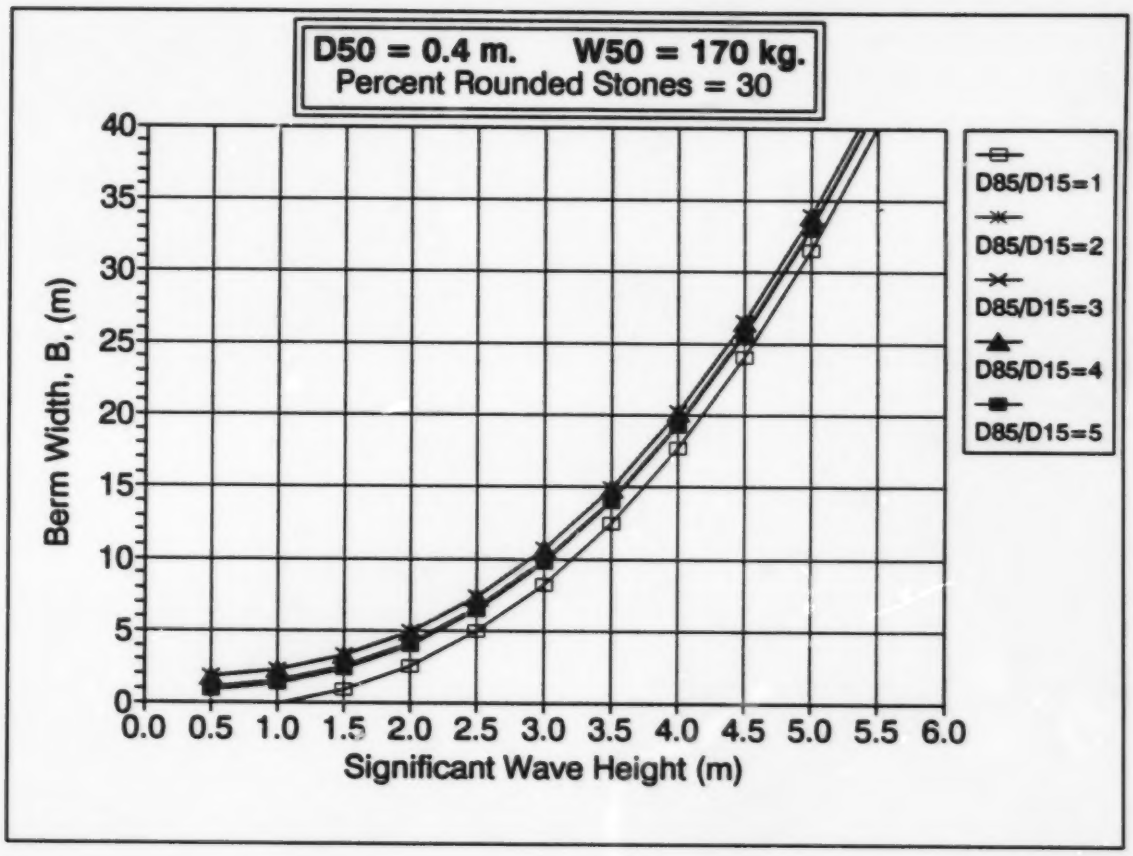
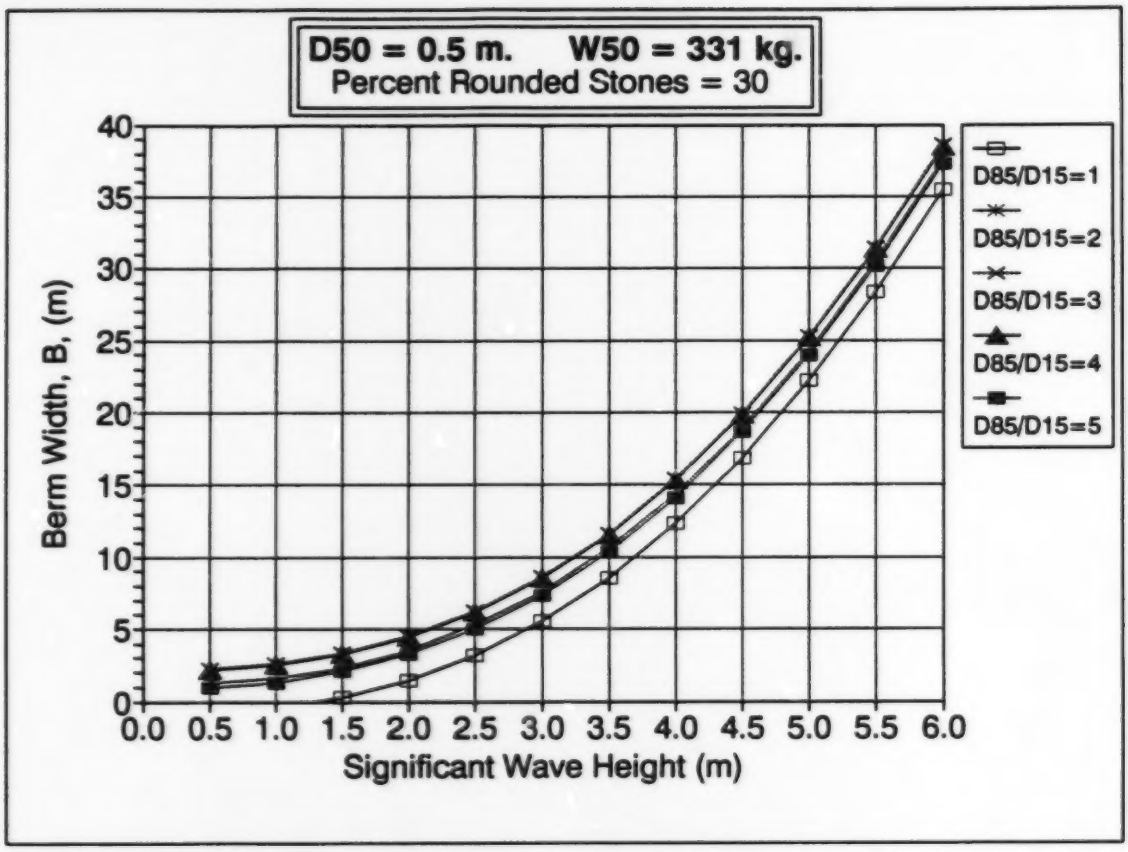
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 0.4 m. W50 = 170 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5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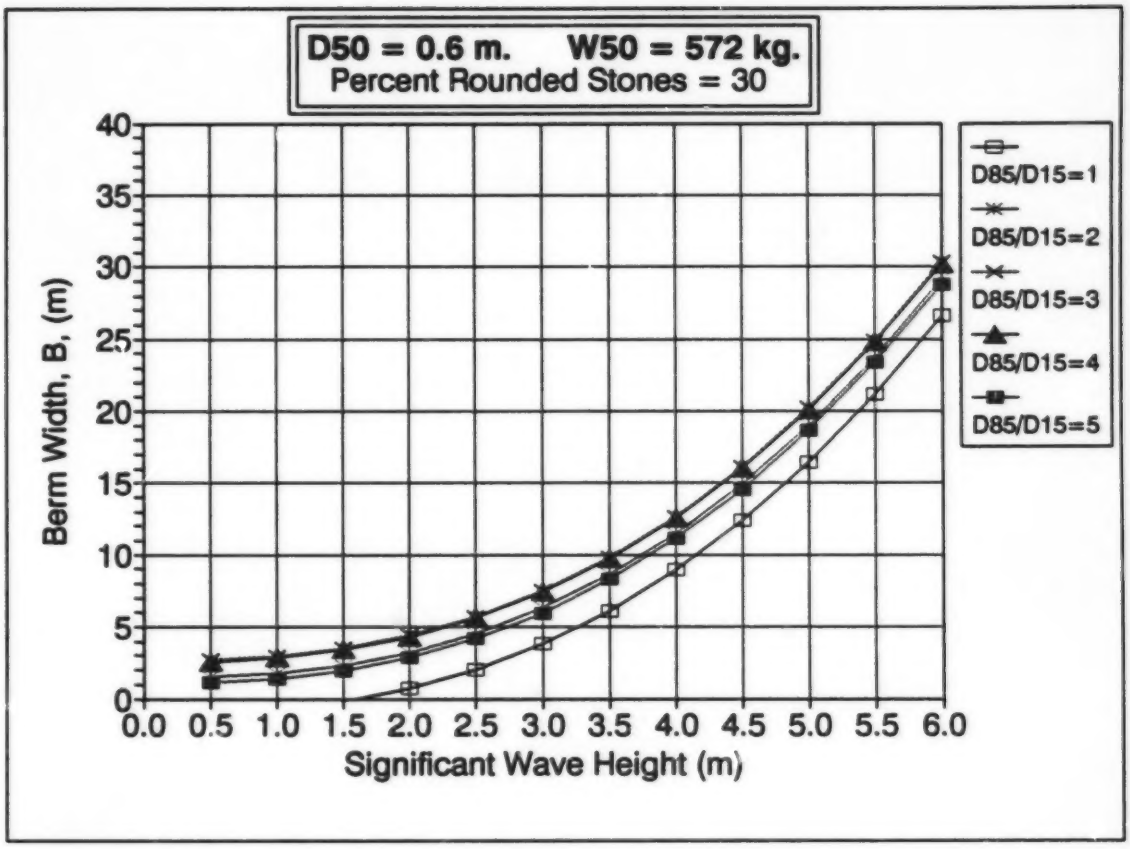
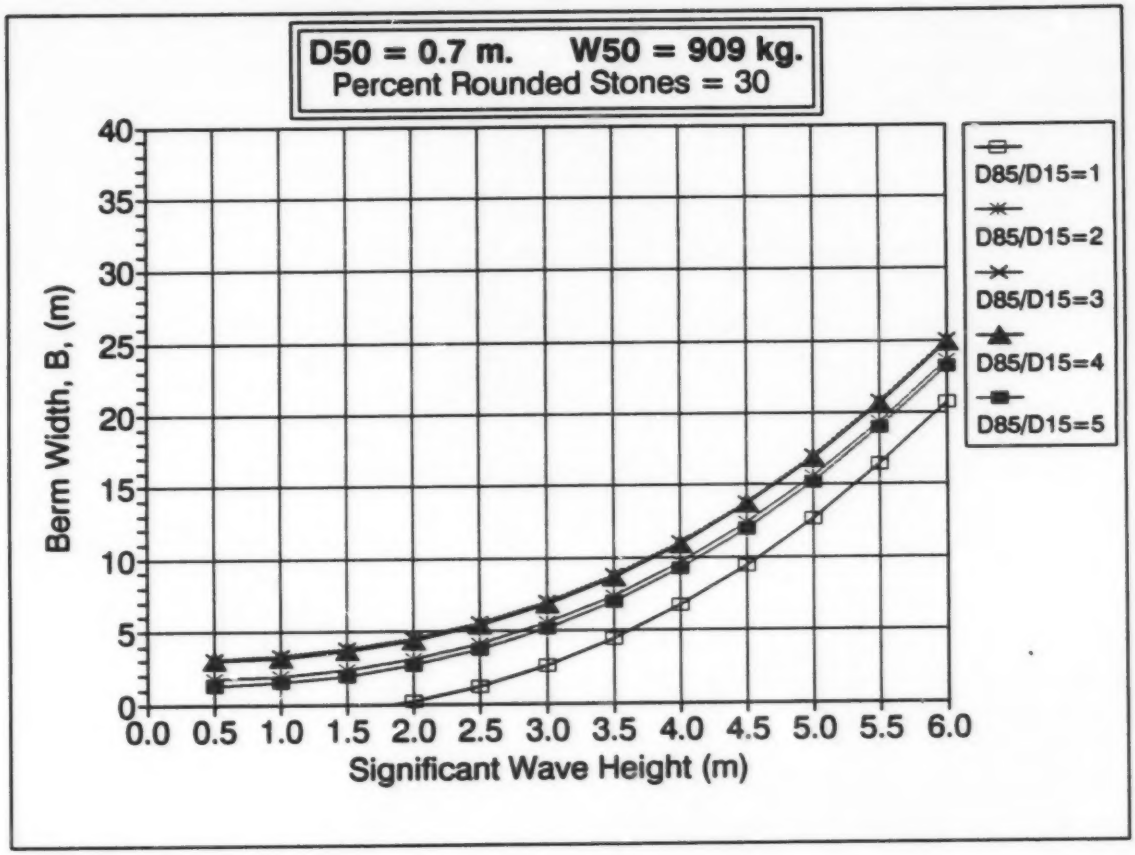
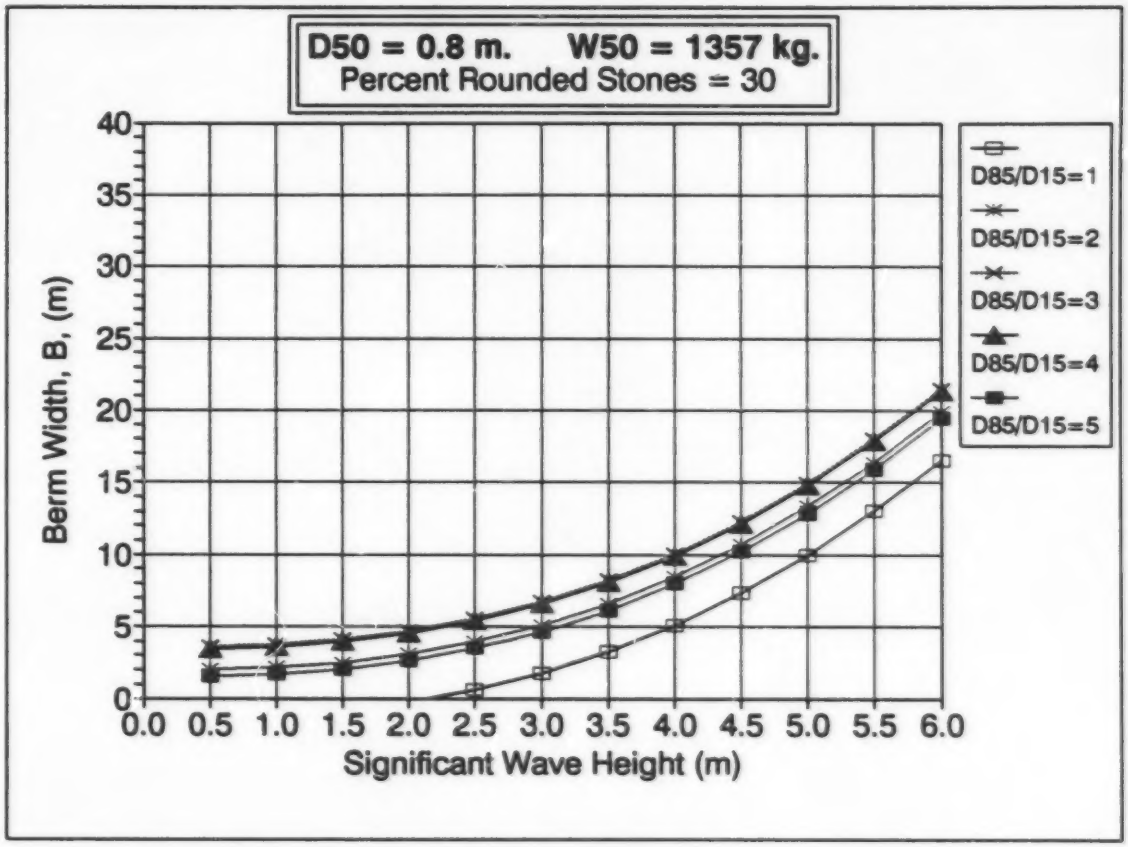
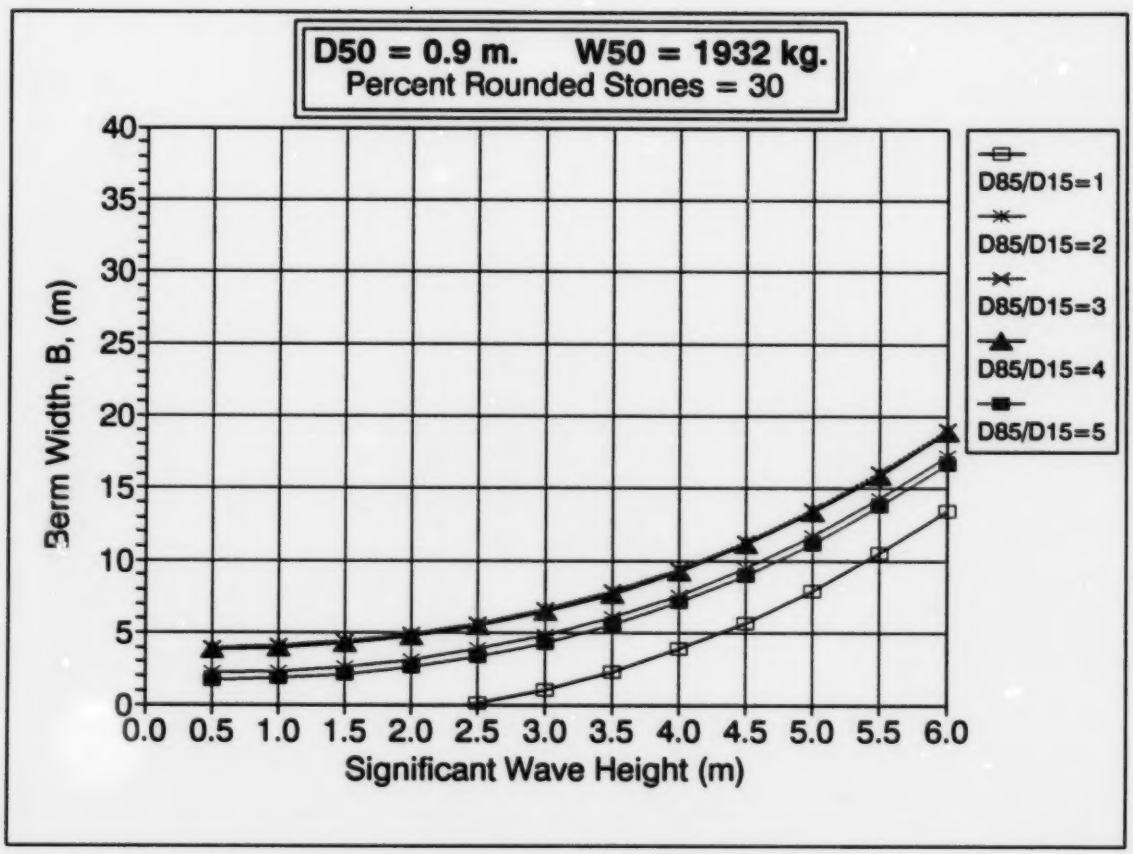
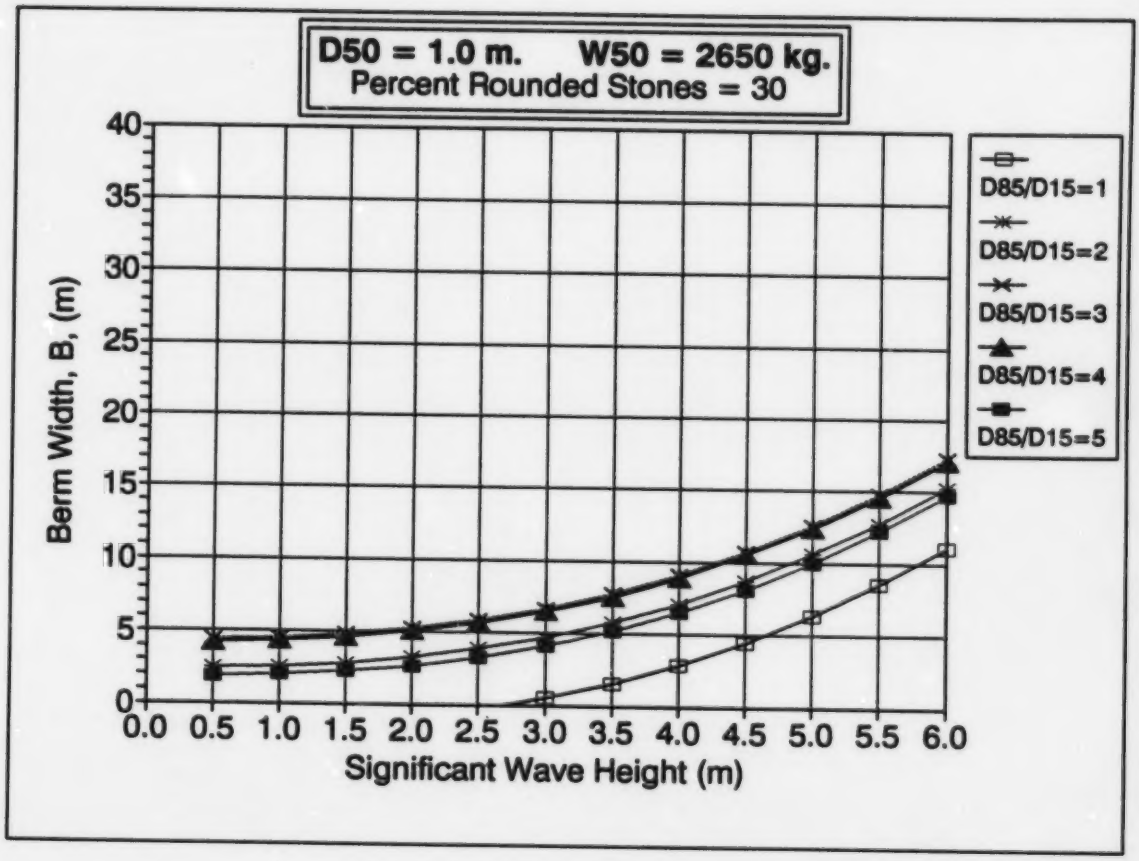
Percent Rounded Stones = 30
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

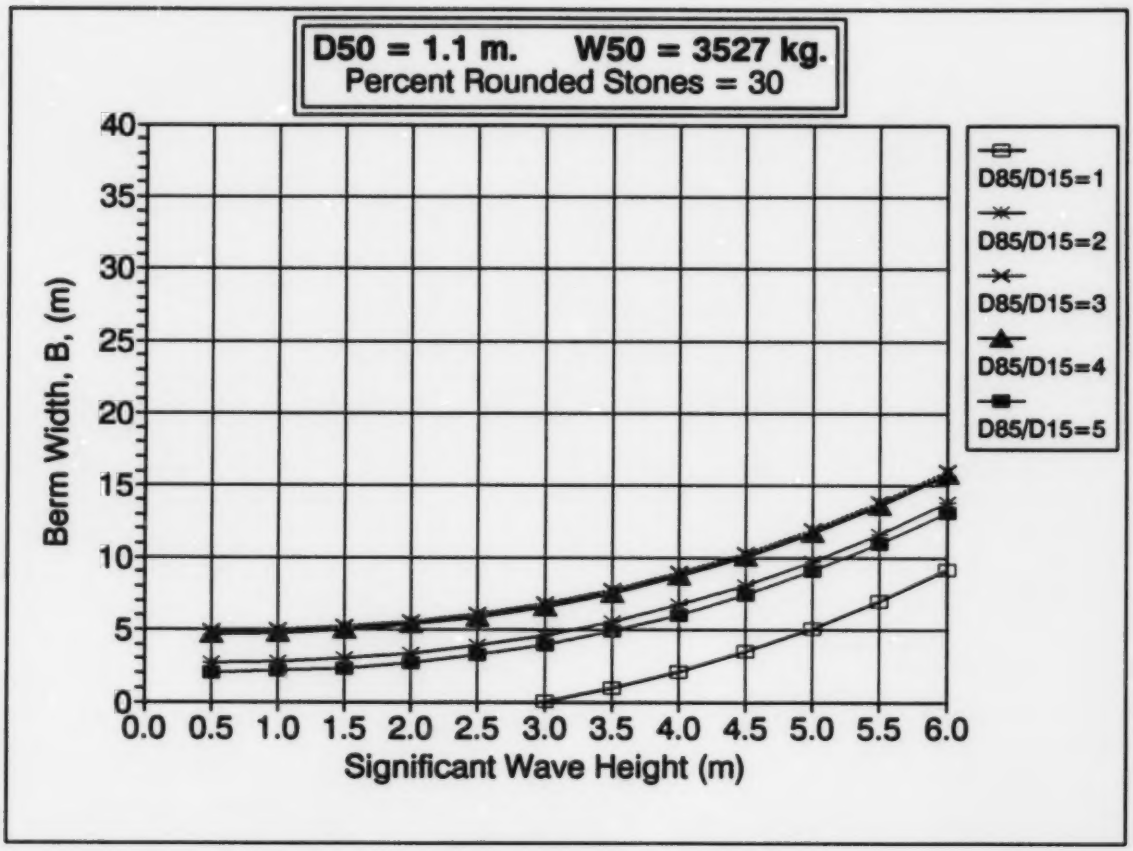

D50 = 0.6 m. W50 = 572 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

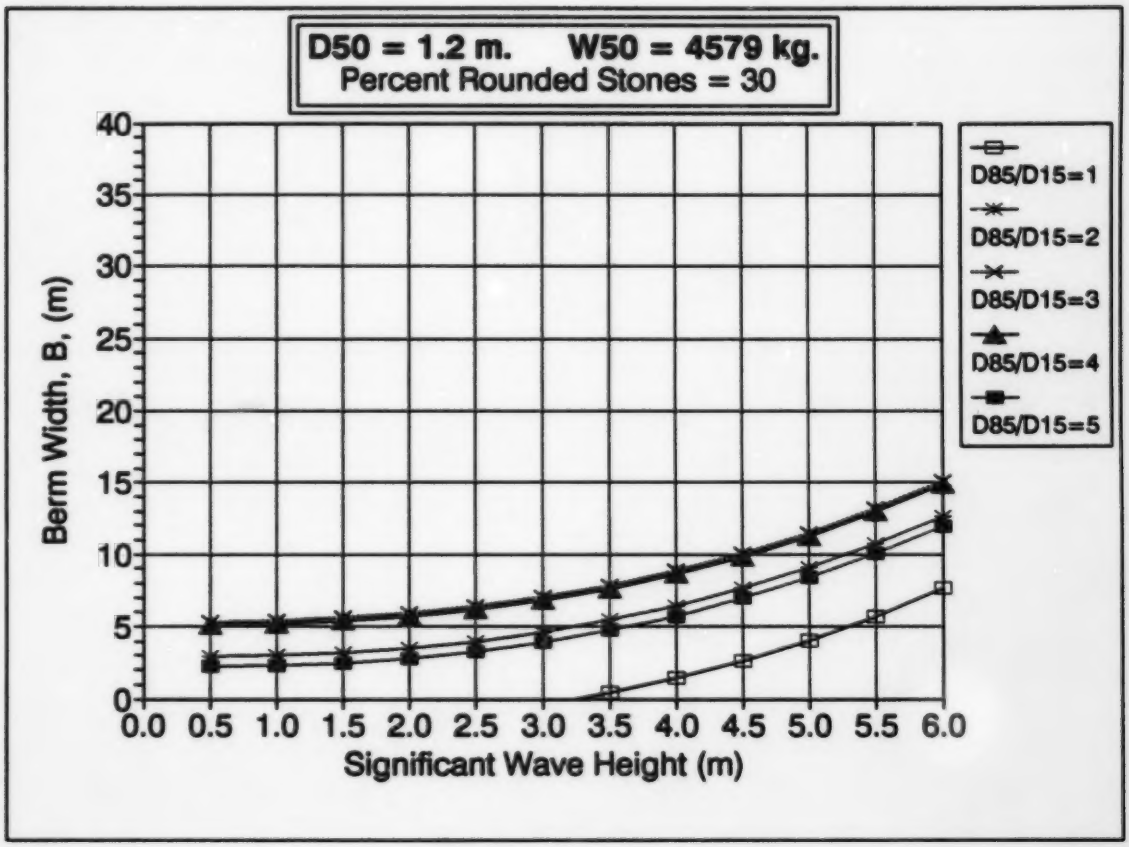

D50 = 0.7 m. W50 = 909 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

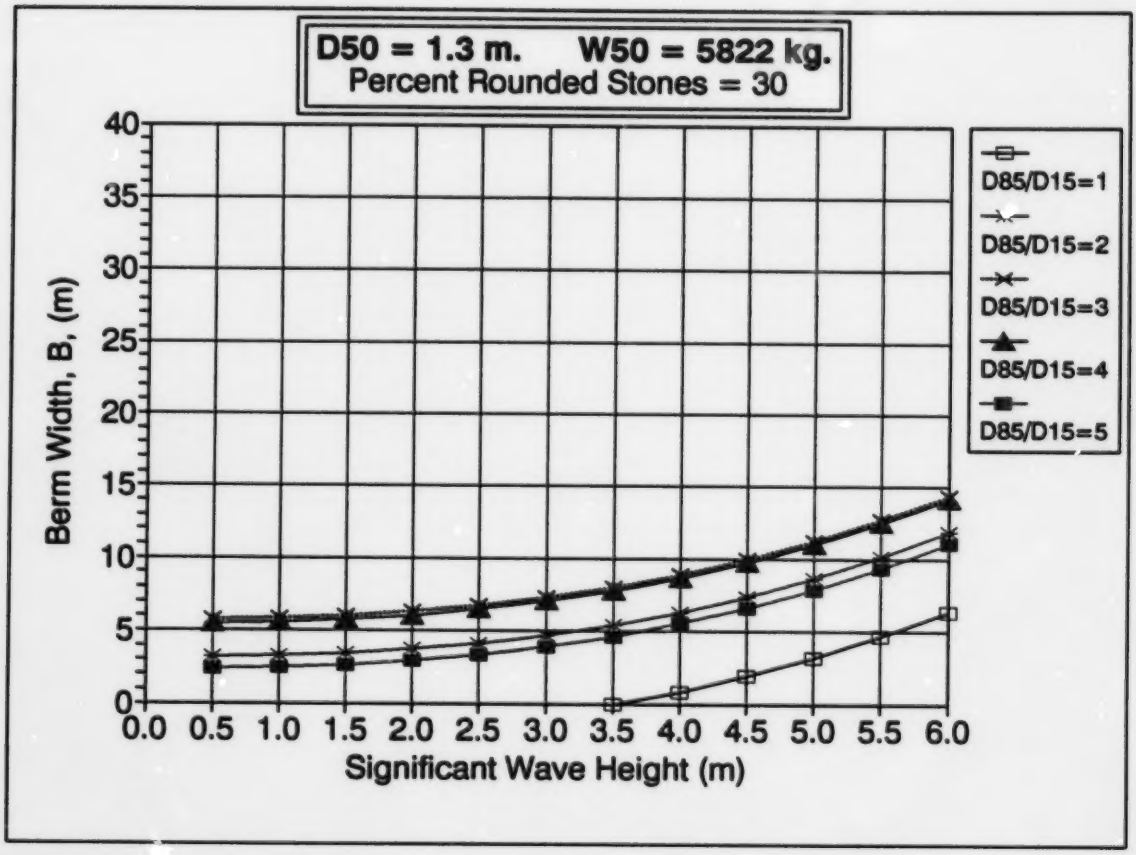

D50 = 0.8 m. W50 = 1357 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 0.9 m. W50 = 1932 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.0 m. W50 = 2650 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.1 m. W50 = 3527 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.2 m. W50 = 4579 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.3 m. W50 = 5822 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

APPENDIX B

CONSTRUCTION SPECIFICATIONS (General Form)

Presented in this chapter is a general form of construction specification. It must be realized that these represent a minimum specification and variation in local conditions from site to site will require modifications to this general specification.

1 GENERAL

The technical specifications in this document refer to the construction of the breakwater at _____ .

The breakwater is to be constructed in accordance to cross-sections specified on Drawing Numbers _____ .

Specifications dealing with material quality and grading, placement geometry, surveying methodology, and section approval are presented below.

2 STONE QUALITY

All quality control inspection must be undertaken at the quarry (in the case of new quarried stone) and at the stockpile (in the case of stones already quarried) prior to loading and transporting material to the breakwater.

All material shall be clean, hard, durable, angular non-friable quarried rock, free from micro-cracks, seams or other defects which may impair durability; free from clay, silt and organic matter. Shale and slate are not acceptable.

Initial checks of quality shall be made visually at the quarry and stockpile by qualified inspectors, under the supervision of a professional geologist. All stone material should be examined.

In addition to the visual inspection,the following tests and limits are to be used in assessing the acceptability of the materials. These tests are to be undertaken at prescribed intervals.

. Relative density (ASTM C-127-84)	2.65 minimum
. Absorption (ASTM C-127-84)	2.0% maximum
. Abrasion Resistance (ASTM C535-B1) maximum loss after 500 revolutions	35%
. Magnesium Sulphate Soundness (ASTM C88-76) maximum loss for 5 cycles	5%
. Freeze/Thaw Resistance (ASTM C-606)	No significant deterioration for 300 cycles.

The material quality tests prescribed above should be undertaken at the commencement of the

project and a milestones determined by intervals of 25% of total production for each of the material gradations. Results must be obtained and relayed to the owner or their consultants within a week of reaching each milestone.

Any material placed within the breakwater and determined to be in disagreement with the prescribed specifications will be removed and replaced at the contractors expense.

Winter quarrying should be discouraged; however, where necessary, the frequency of quality control tests should be increased.

3 STONE GRADING

All classes of material shall be well graded within the limits specified in the Table B.1[1]. For all armour stones classes the maximum dimension of a stone should not exceed 2.5 times the minimum dimension. All gradations are described by a per cent greater than; the per cent referring to per cent by weight. The maximum allowable tolerance has been incorporated into the prescribed gradation range. Material not falling within the range specified will not be accepted. These specifications are based on stability requirements determined during the design phase. No substitutions will be accepted.

The following gradation checks must be carried out:

1. Individual stones in a truckload shall be checked at random to ensure that they fall within the prescribed size range. This is a visual check and should be done while the trucks are being loaded. Each truck load should be checked in this manner. Should undersize material be found, the truck should be dumped into a spoil-pile. Resorting of material in this pile is allowable.

2. A full gradation analysis shall be undertaken at milestone levels determined by intervals of 20% of total weight of material produced for each class. The minimum sample size should be 200 tonnes. All classes of material should be checked in this manner.

3. Spot checks will be carried out at the breakwater site. Any loads deemed to contain undersized material shall be rejected and returned to the spoil-pile. Should any particular truck be rejected, then all further truckloads must be inspected prior to dumping until the inspector is sure that the contaminated truck was an isolated incident. Should four consecutive trucks be found to be carrying undersize material, production at the quarry and/or stockpile should be halted until a reason for the "contamination" is found and corrected. All stone placed that day should be inspected in-situ to ensure that it falls within allowable limits.

---

[1] Note, tables (and figures) should be developed for each grading of material. Gradation curves should be based on a minimum of 5 points between maximum and minimum stone size.

Table B.1 Example of Gradation Table with Limits

Stone Mass (kg)	Per Cent Greater
300	96 to 100
500	80 to 100
1000	55 to 75
2000	20 to 40
3000	5 to 25
3500	0 to 20
4000	0 to 14

4 MATERIAL PLACEMENT

The breakwater shall be constructed to the dimensions shown on Drawings _____.

An elevations given in the design drawings refer to FINAL ELEVATIONS, that is after all settlement associated with the underlying foundation material and normal "shakedown" of the mound is accounted for.

Placement of Core Stone

Material shall be placed to the limits and dimensions shown on the drawings. It must be ensured that there is an even distribution of stone sizes throughout the work with no pockets of fine material. Material must not be placed outside the specified limits. Placement of core material should not extend more than 15 metres beyond the armour protection.

Placement of berm armour

Armour stone shall not be placed until the slopes of the core stone have been approved by the inspectors. The material must be placed and shaped to achieve the lines and grades shown on the design drawings. Armour stone may be placed by end dumping or other bulk placement methods. Individual placement, while acceptable is not necessary. The placement method utilized must limit the breakage rate of armour stone.

5 SURVEYS

Surveys shall be undertaken on a 10 metre grid along the longitudinal axis of the breakwater. Individual profile lines should be measured by surveying the top elevation of each stone in the case of armour stones and on a 1 metre grid in the case of core stone.

Surveys should be completed using standard levelling and chaining techniques. The survey rod for the berm armour shall contain a baseplate having the diameter equal to the median size of the armour stone material.

Crest stones shall have average elevations higher or equal to the design crest elevation. The minimum elevation of the highest point of any one stone should be less than 15 cm under the design crest elevation. However, only up to 20% of the stones should have minimum elevation of the highest point below the design crest elevation and no two consecutive stones should have minimum elevation of the highest point below the design crest elevation. The stone located on each edge of the crest of the breakwater shall have its highest point elevation equal to the design crest elevation or higher.

Tolerances for the control of the individual stones placed on the design slopes should be ±30 cm vertically from the design slope line and ± 0.5 m horizontally from the design slope line. A minimum of 10 stones should be surveyed, along a minimum horizontal distance of 25 m from the edge of the design crest elevation line.

Should any section be found to be deficient, this section will be brought up to standard immediately.

6 CONSTRUCTION

Contamination

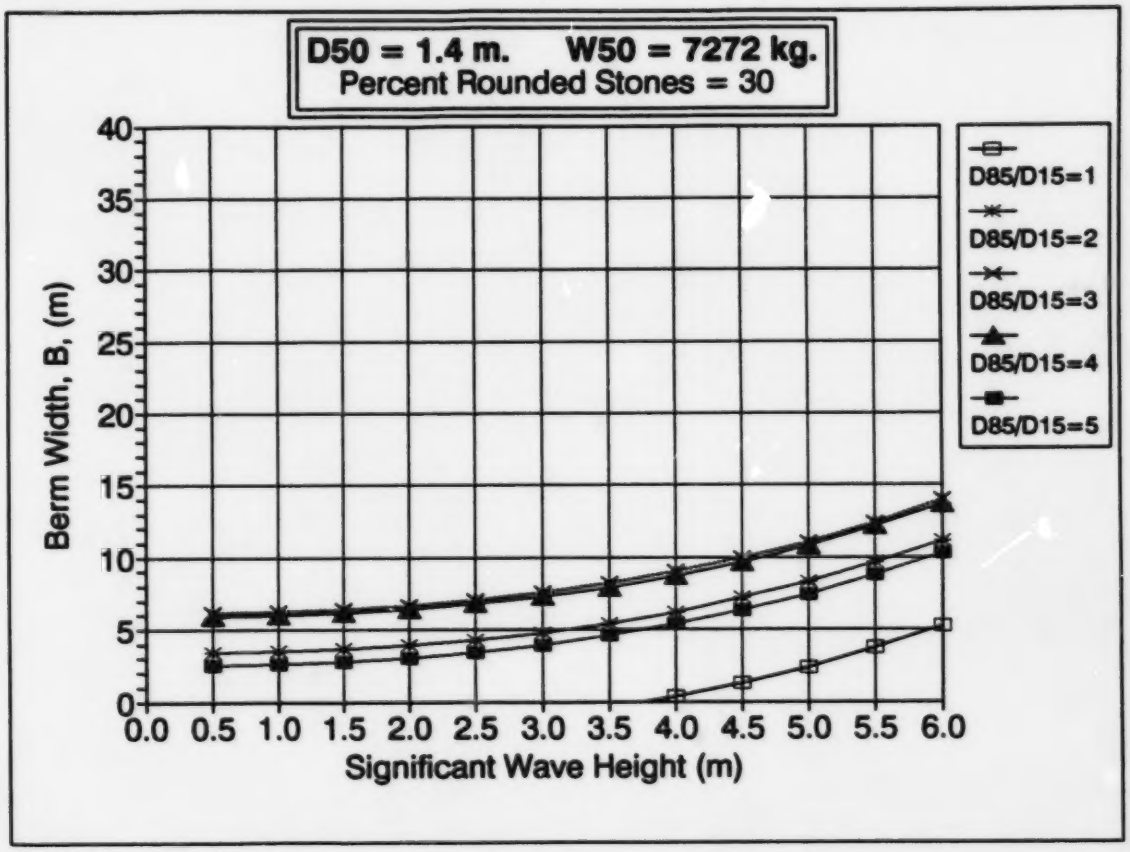
- extension of a construction roadway over any of the armour class materials is allowable providing 100% recovery of the roadway material is achieved prior to completion of the project. Close supervision during removal must be given a high priority.

Temporary protection against storm wave damage

- for temporary protection of the exposed core during construction two layers of armour stone could be placed. This emergency procedure may be repeated up to 4 times along the length of the breakwater. This material does not need to be removed when construction resumes.

Monitoring procedures

- after construction of the breakwater periodical monitoring of the structure is recommended with the objective of reviewing its performance.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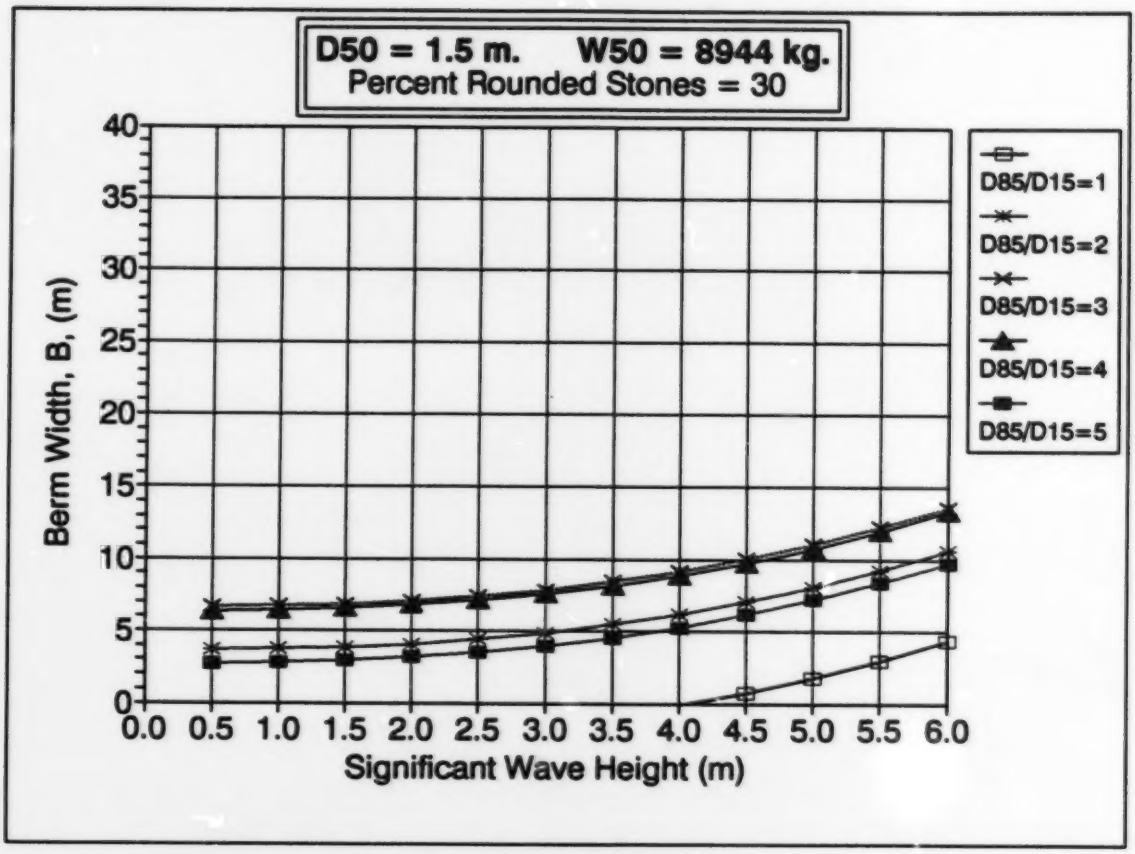
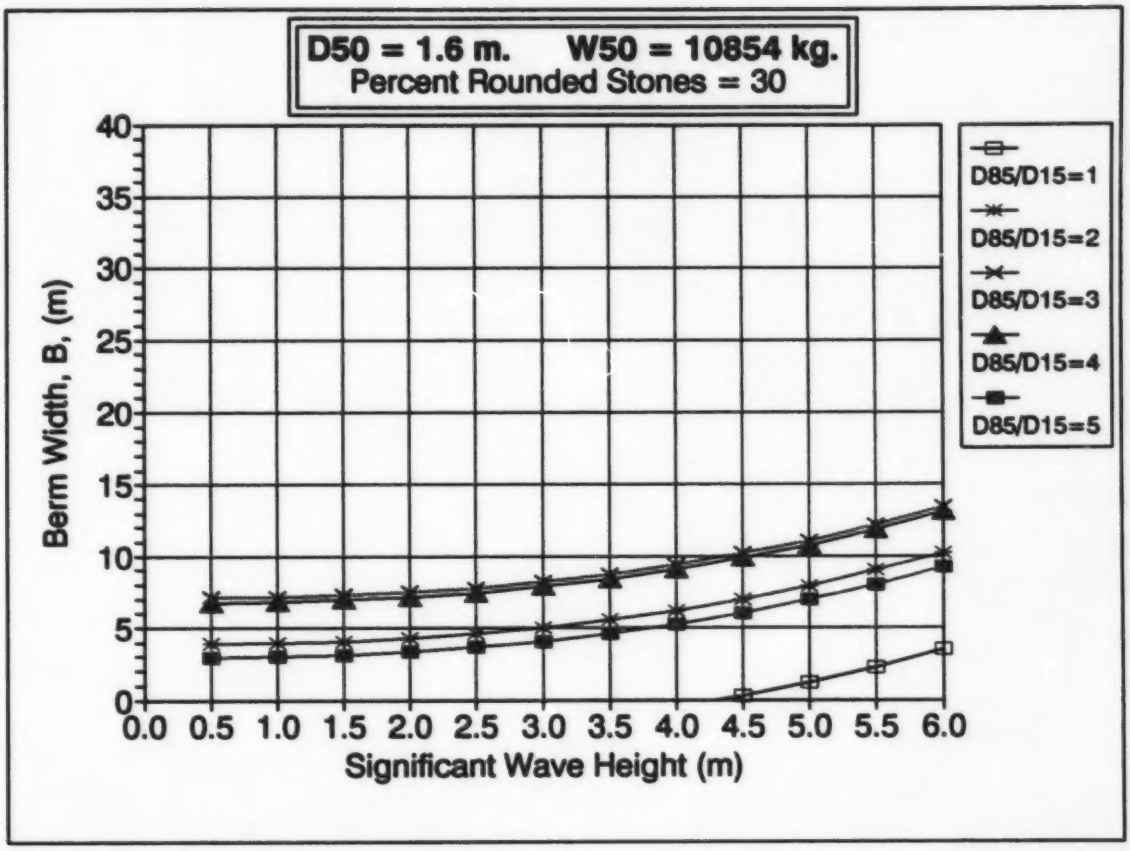
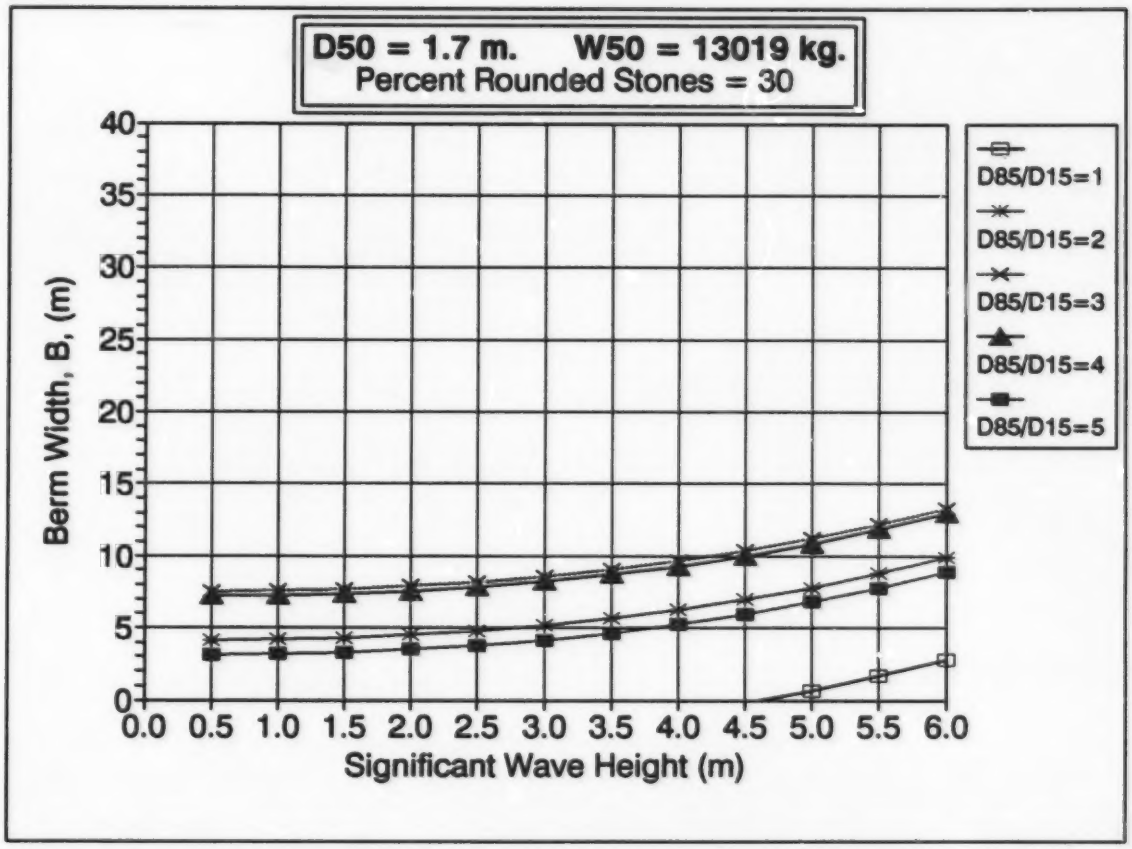
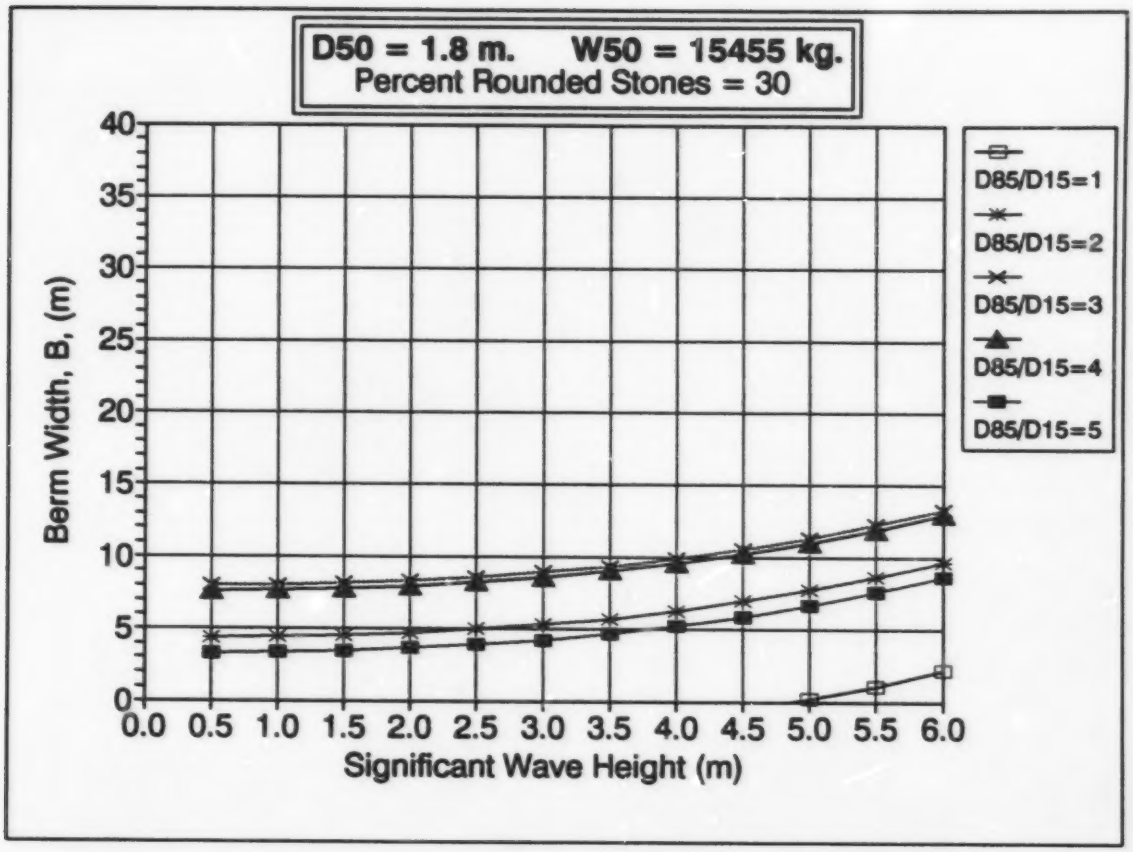
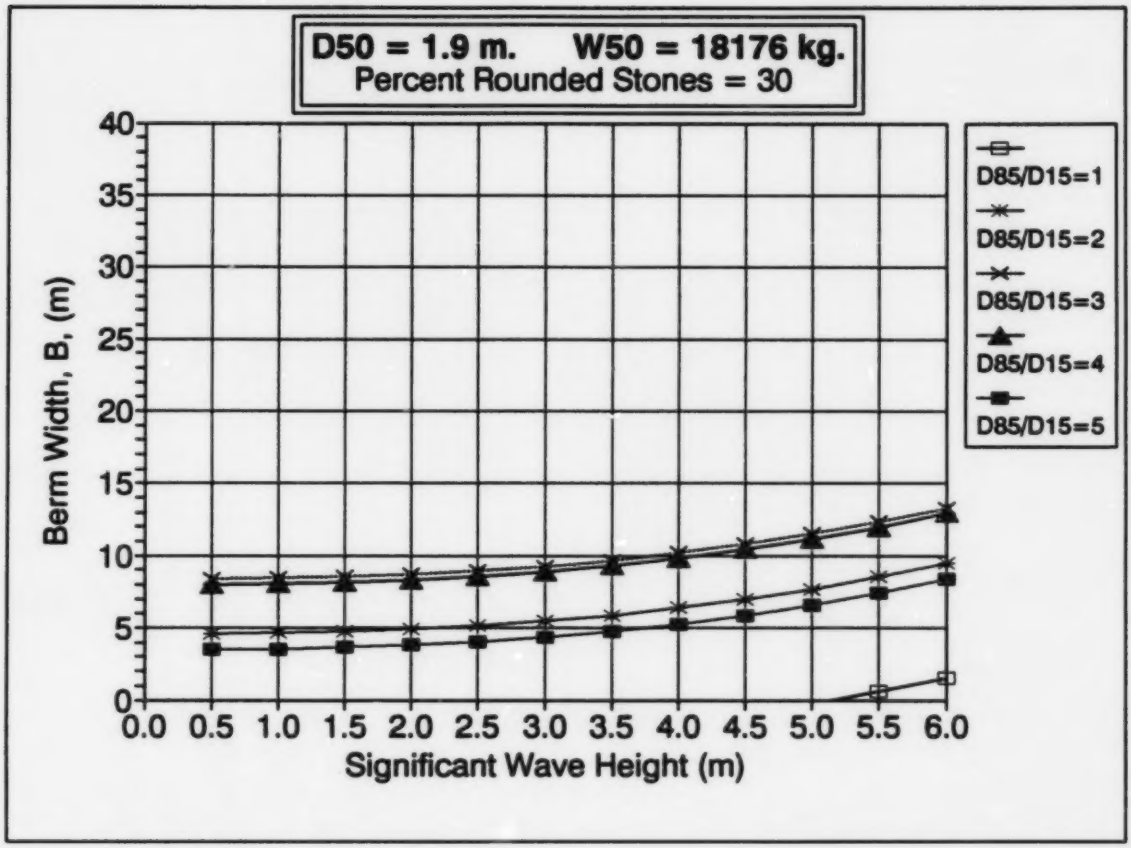
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

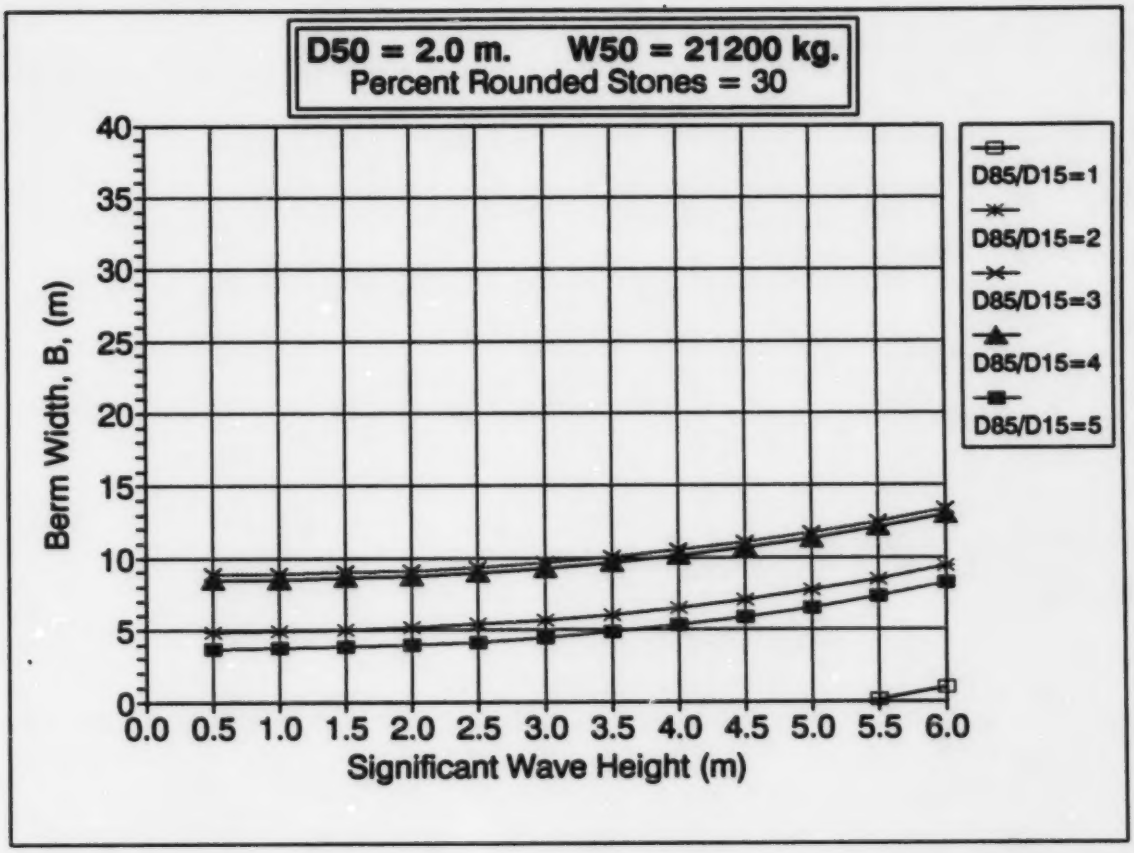

D50 = 1.5 m. W50 = 8944 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

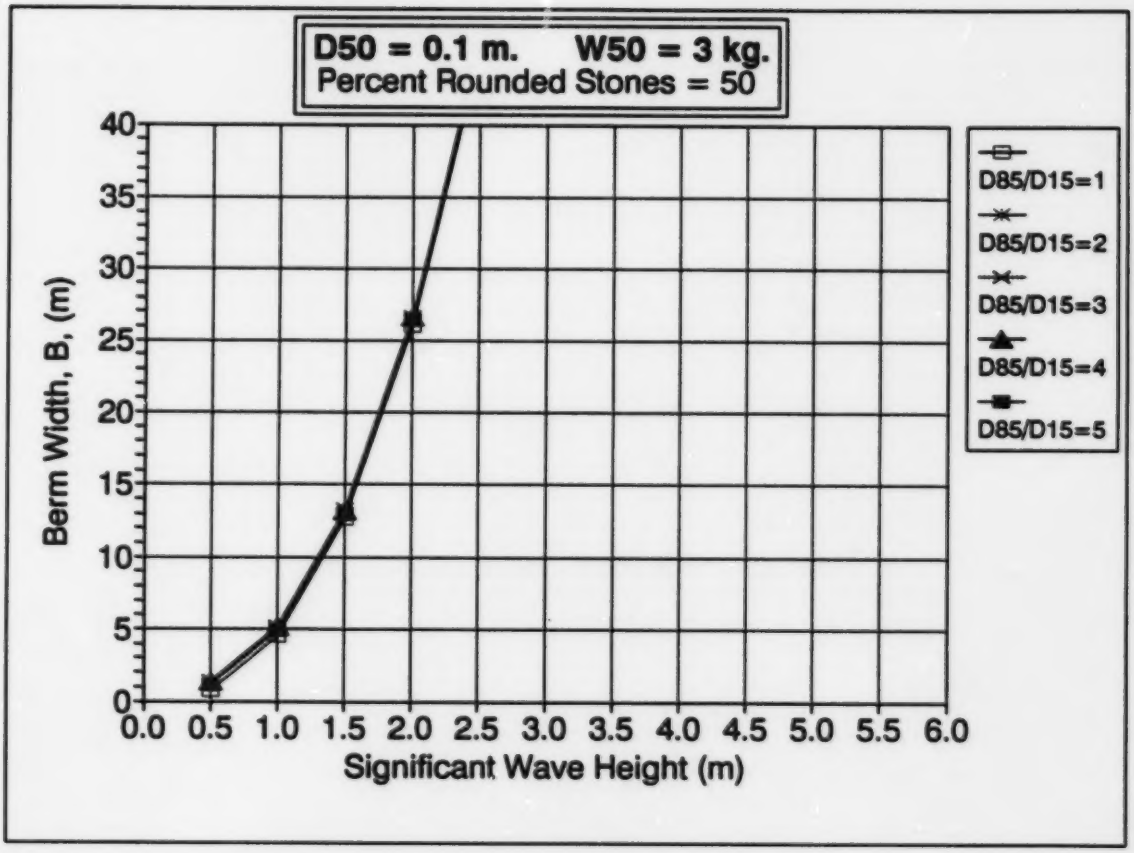

D50 = 1.6 m. W50 = 10854 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.7 m. W50 = 13019 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.8 m. W50 = 15455 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.9 m. W50 = 18176 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 2.0 m. W50 = 21200 kg.
Percent Rounded Stones = 30
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 0.1 m. W50 = 3 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
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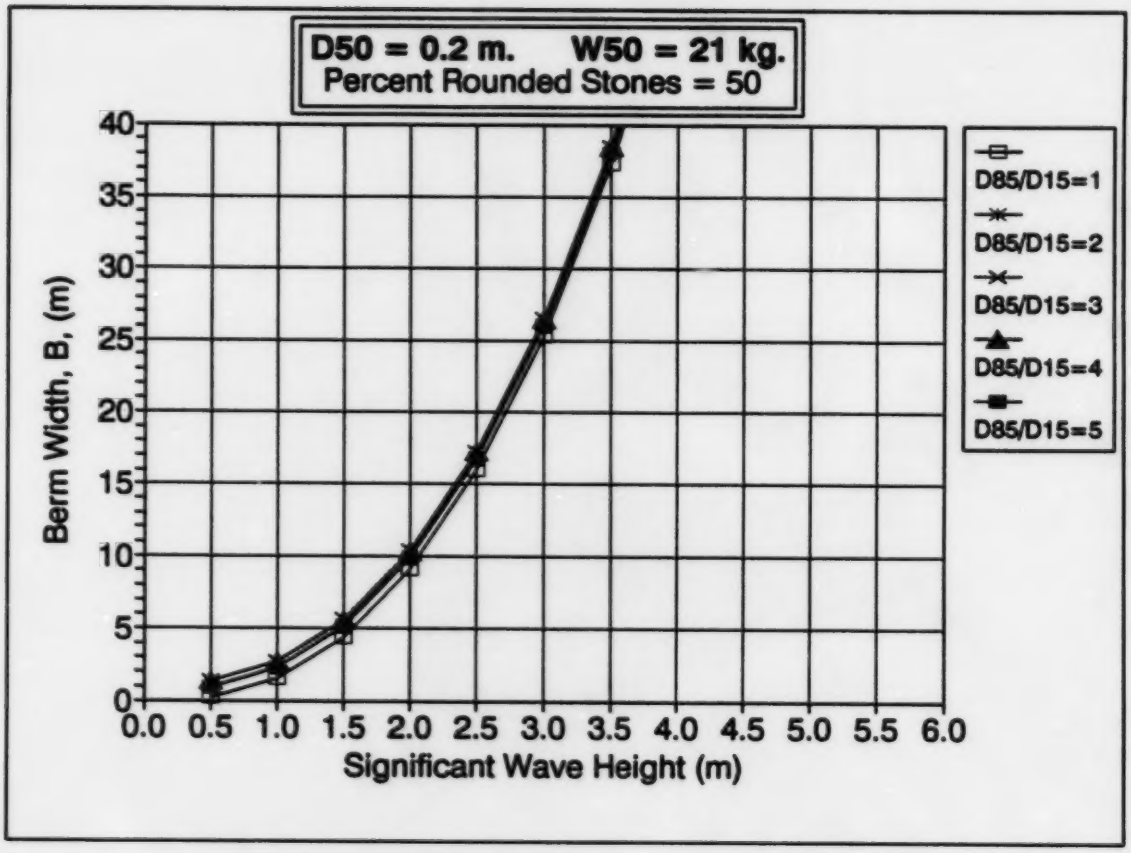
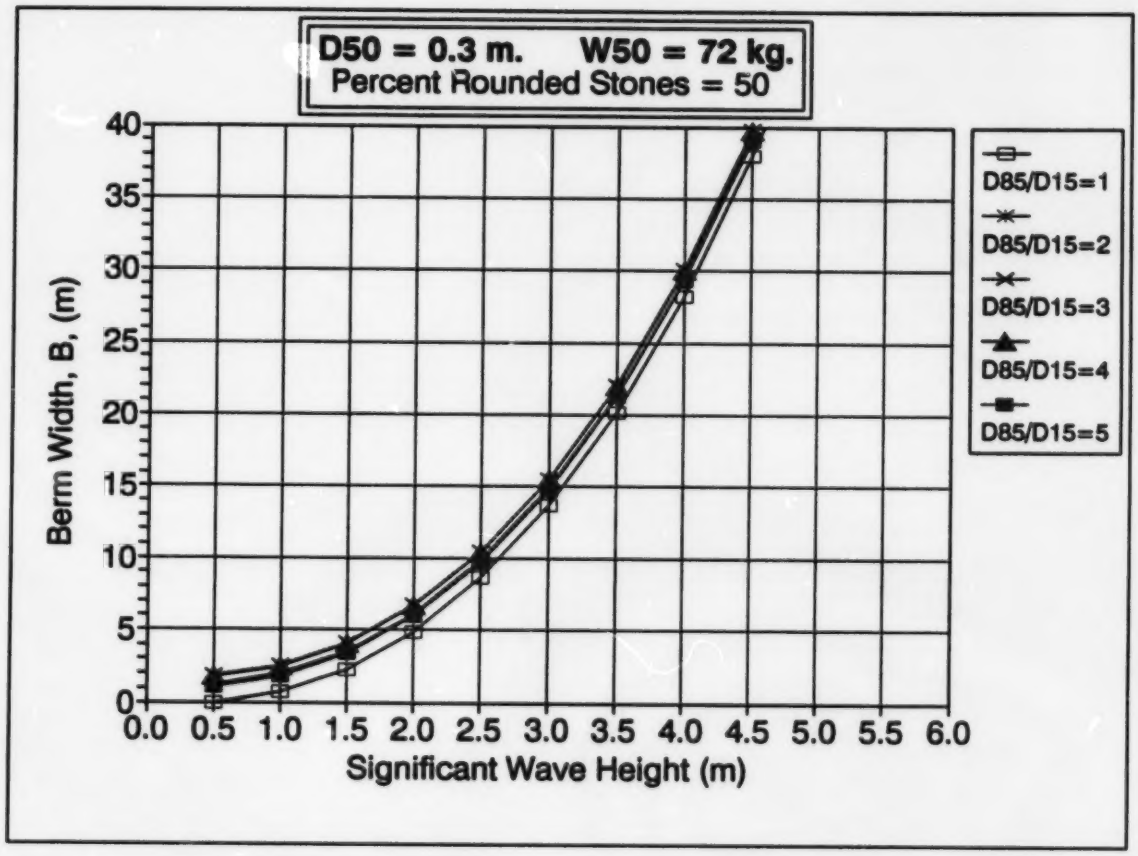
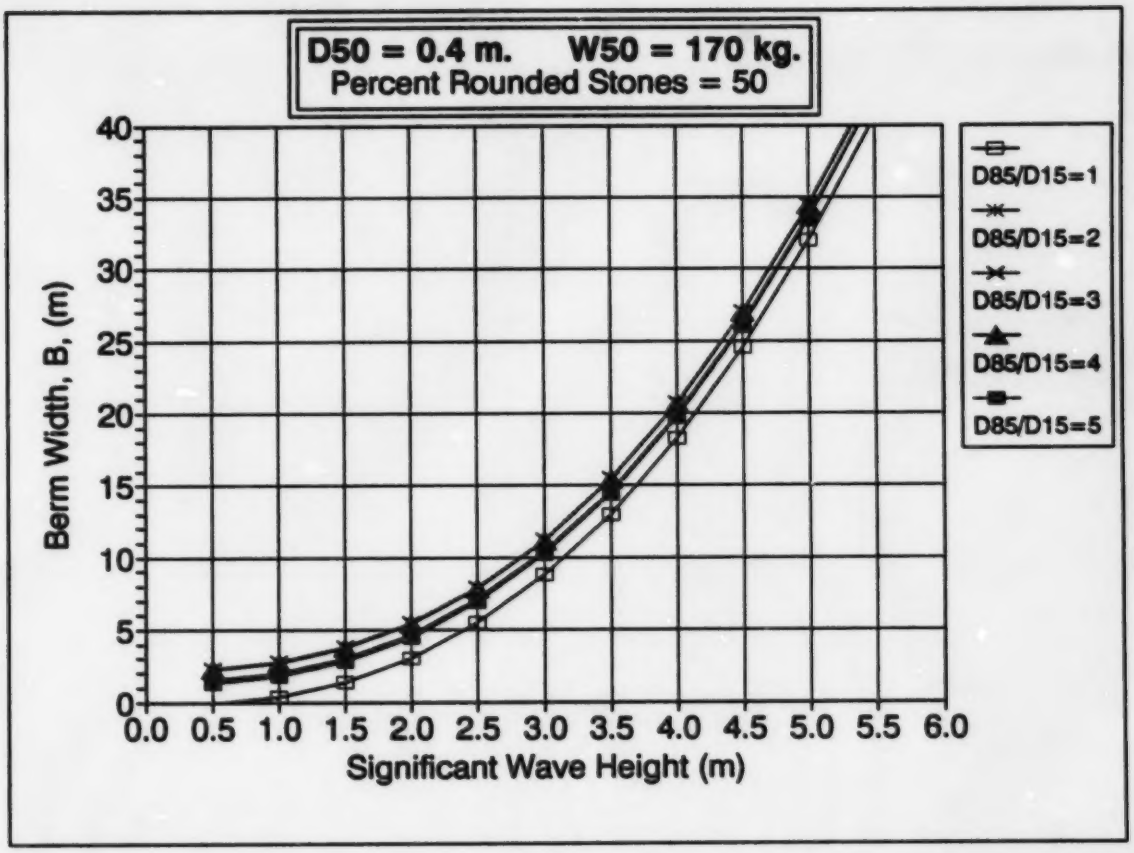
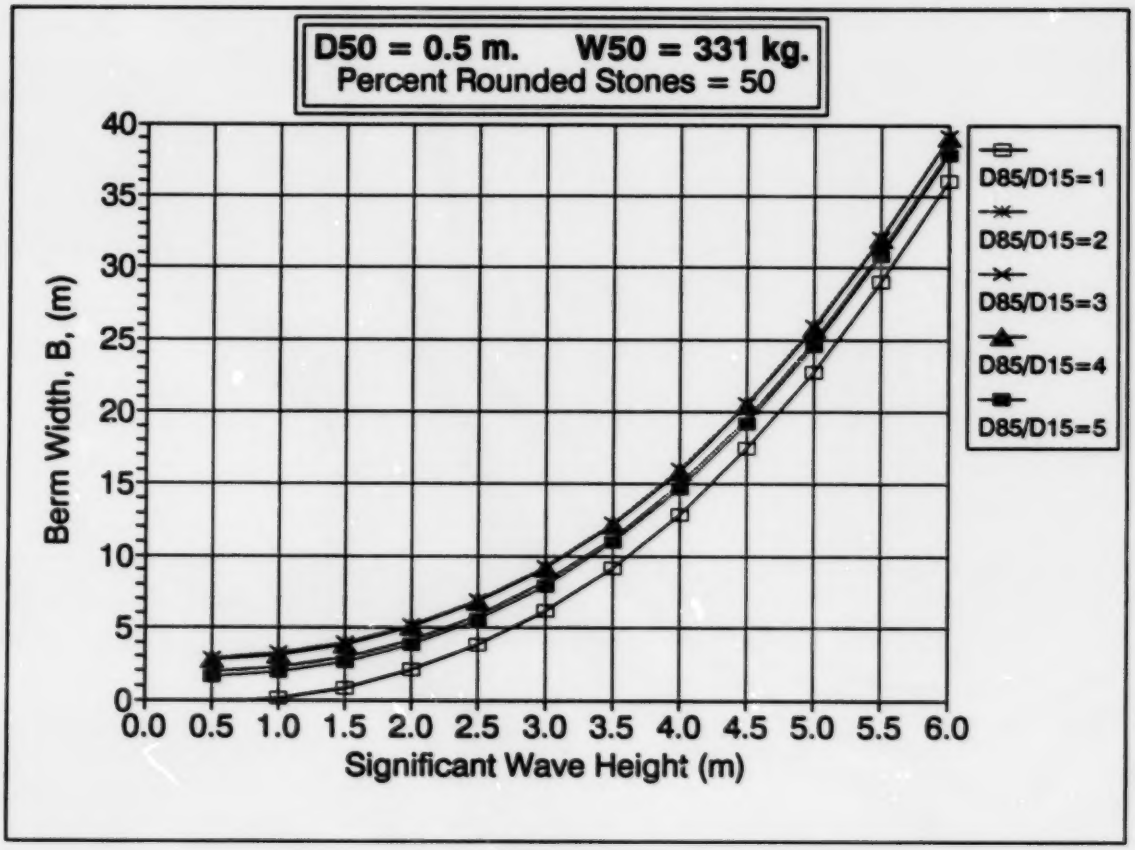
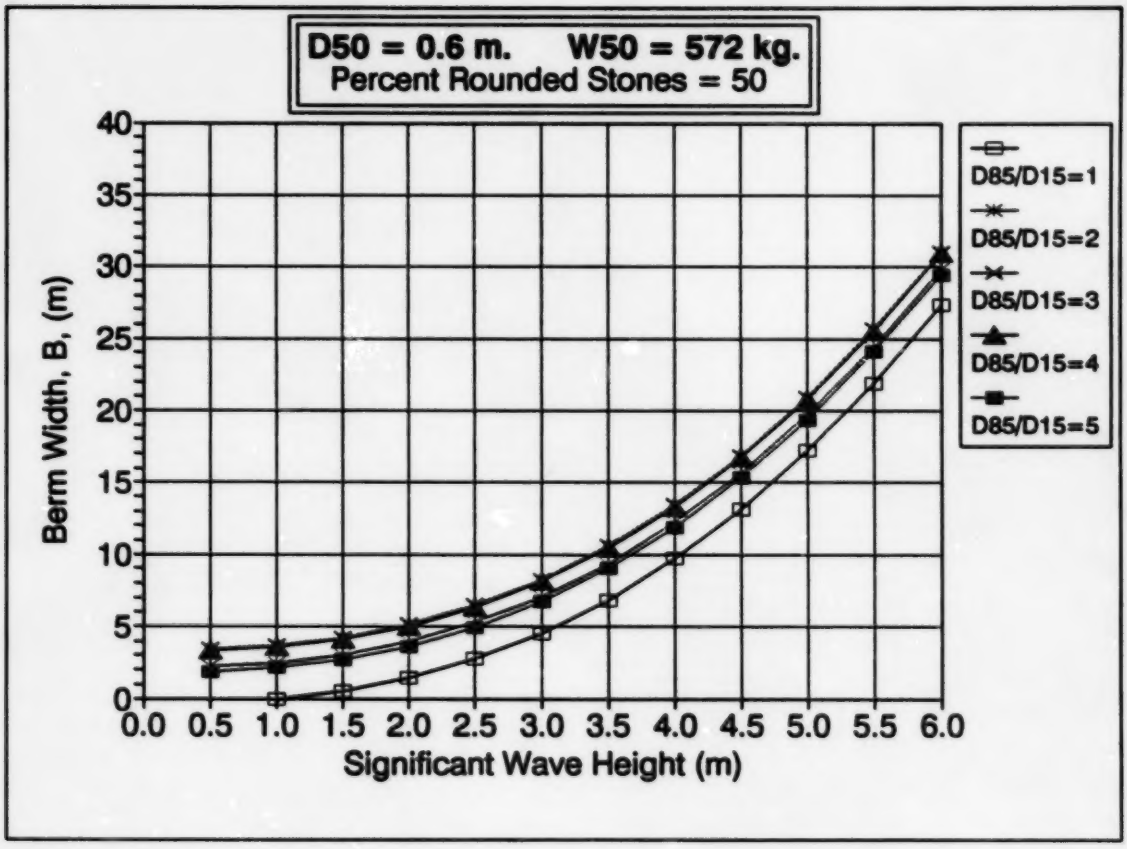
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

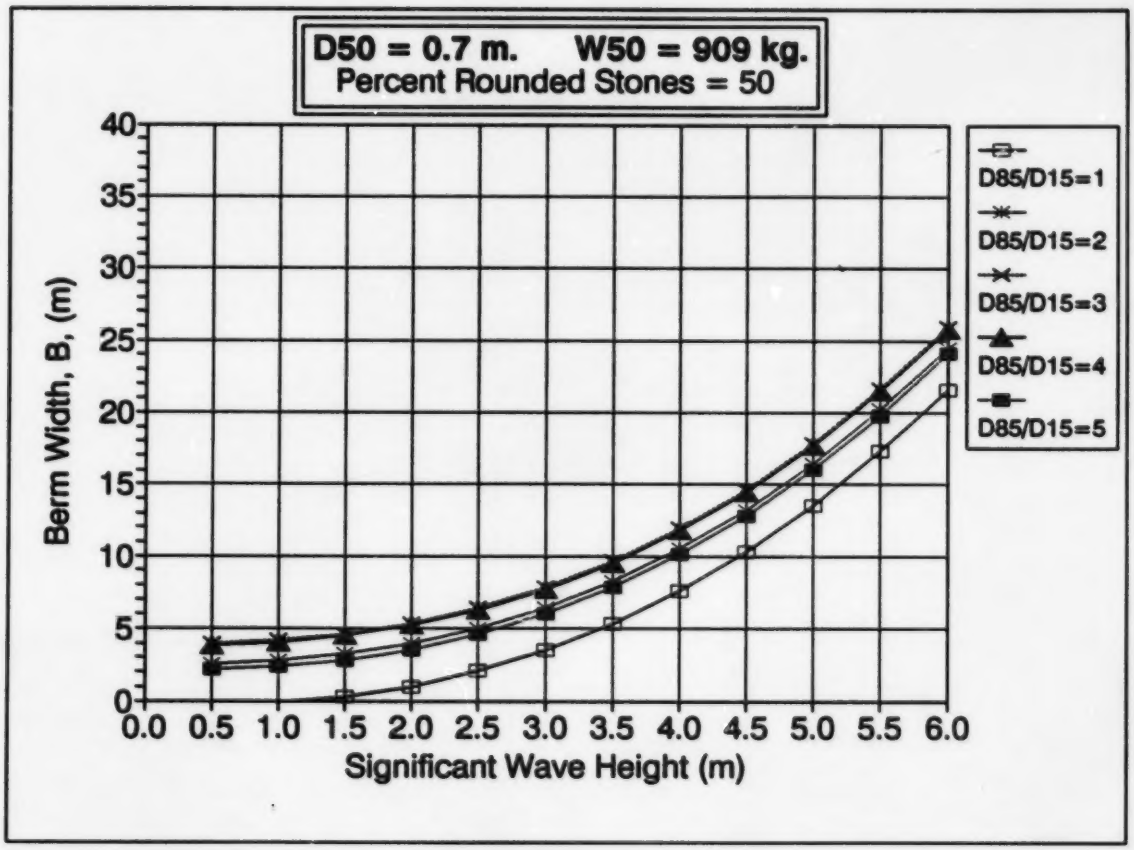

D50 = 0.2 m. W50 = 21 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

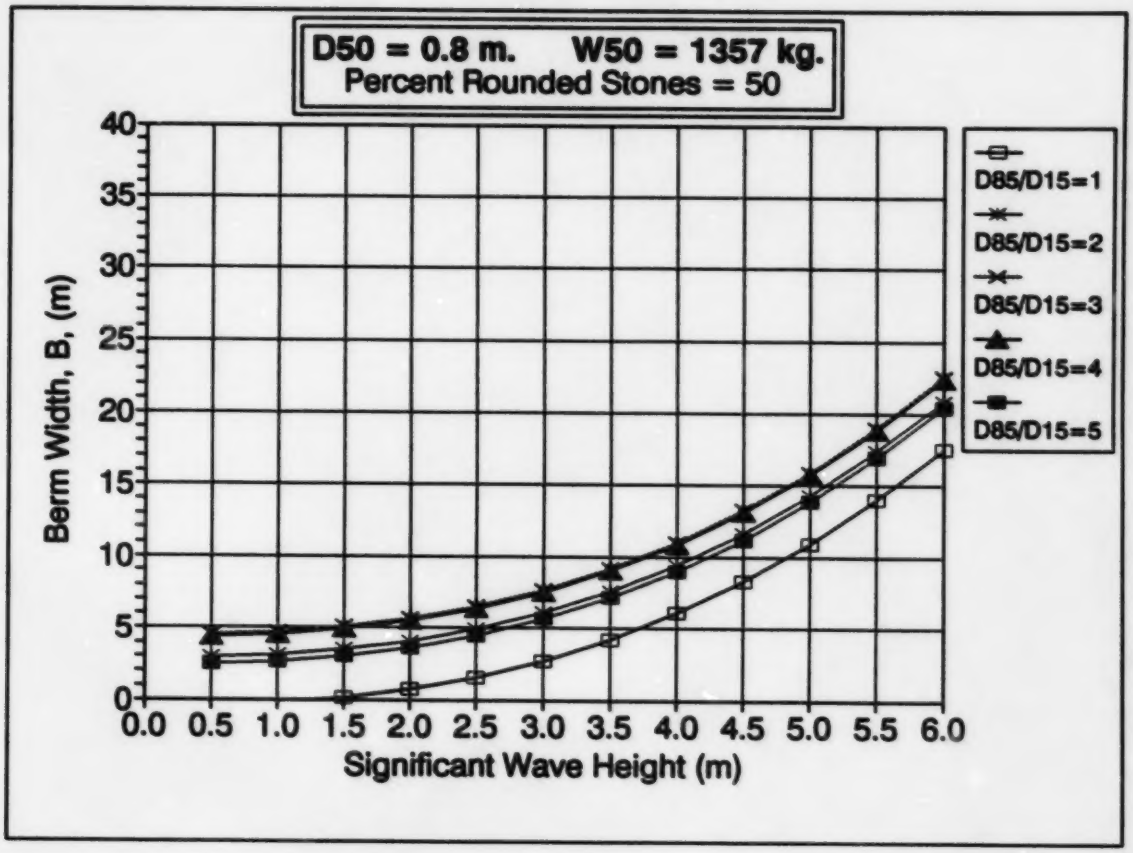

D50 = 0.3 m. W50 = 72 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

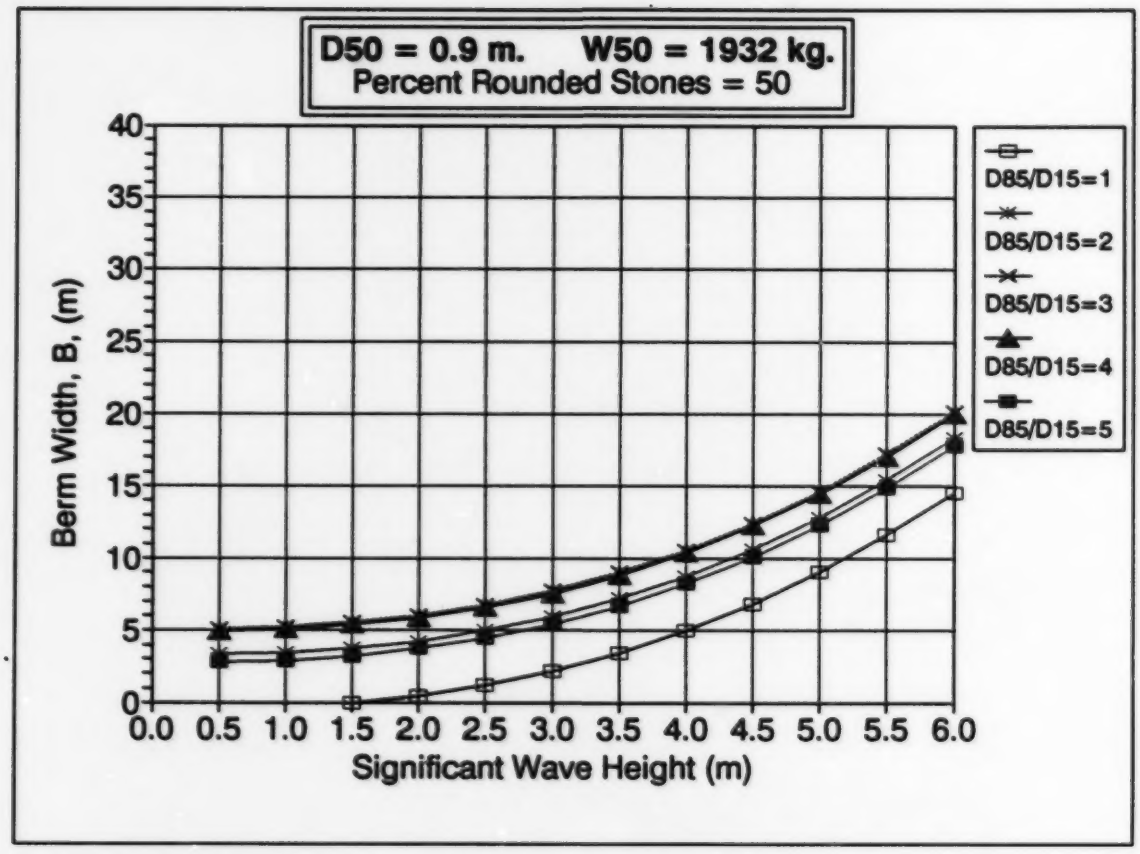

D50 = 0.4 m. W50 = 170 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

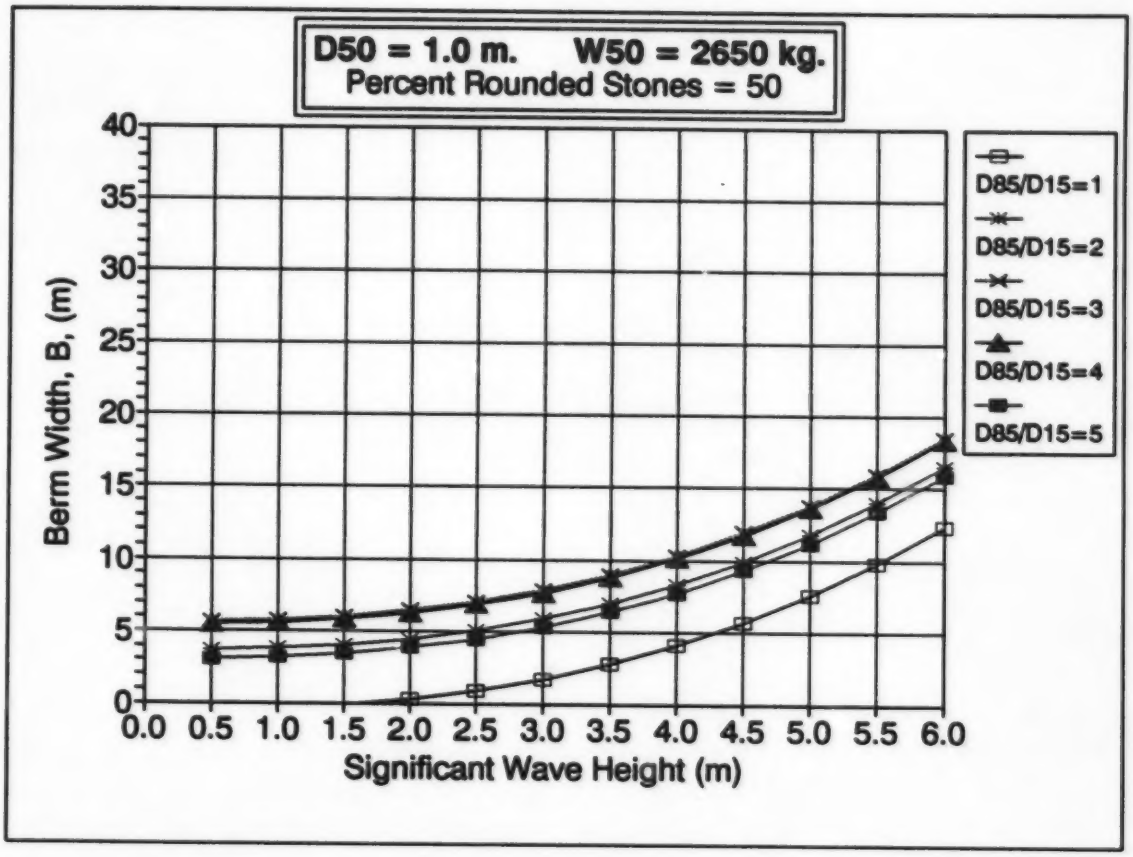

D50 = 0.5 m. W50 = 331 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

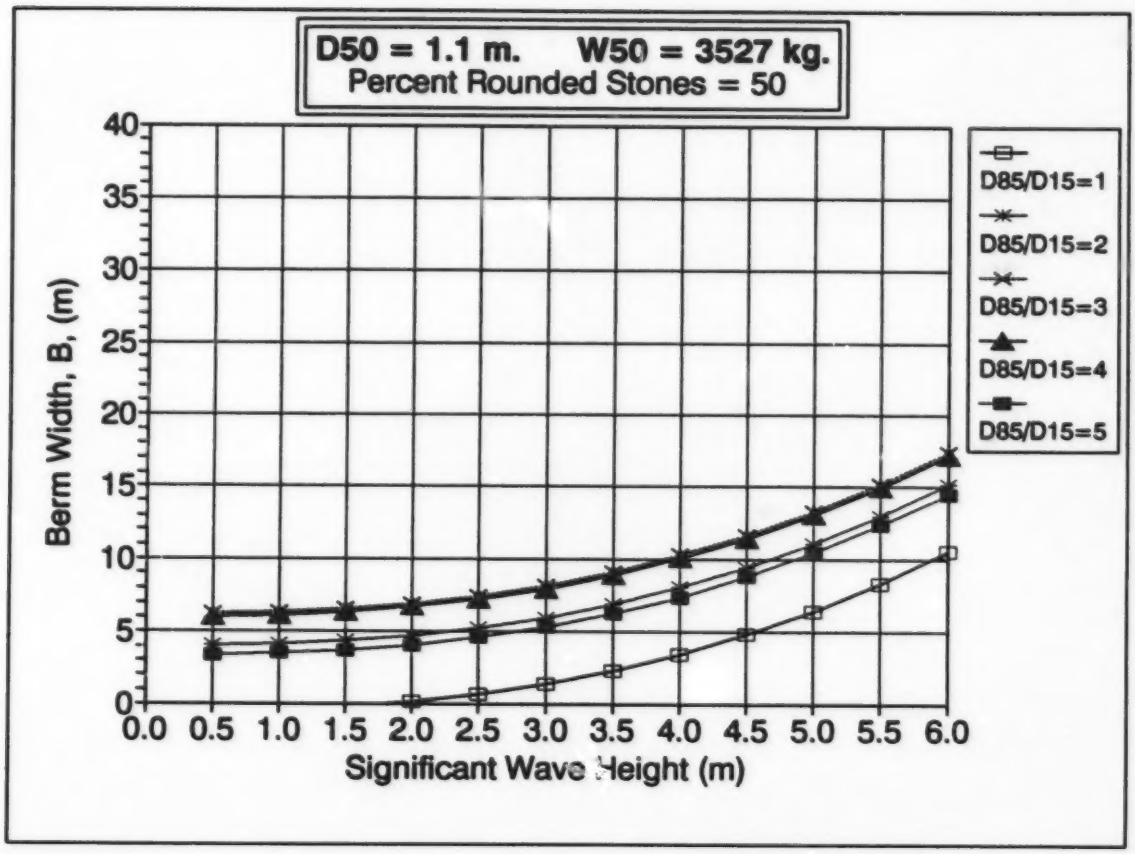

D50 = 0.6 m. W50 = 572 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

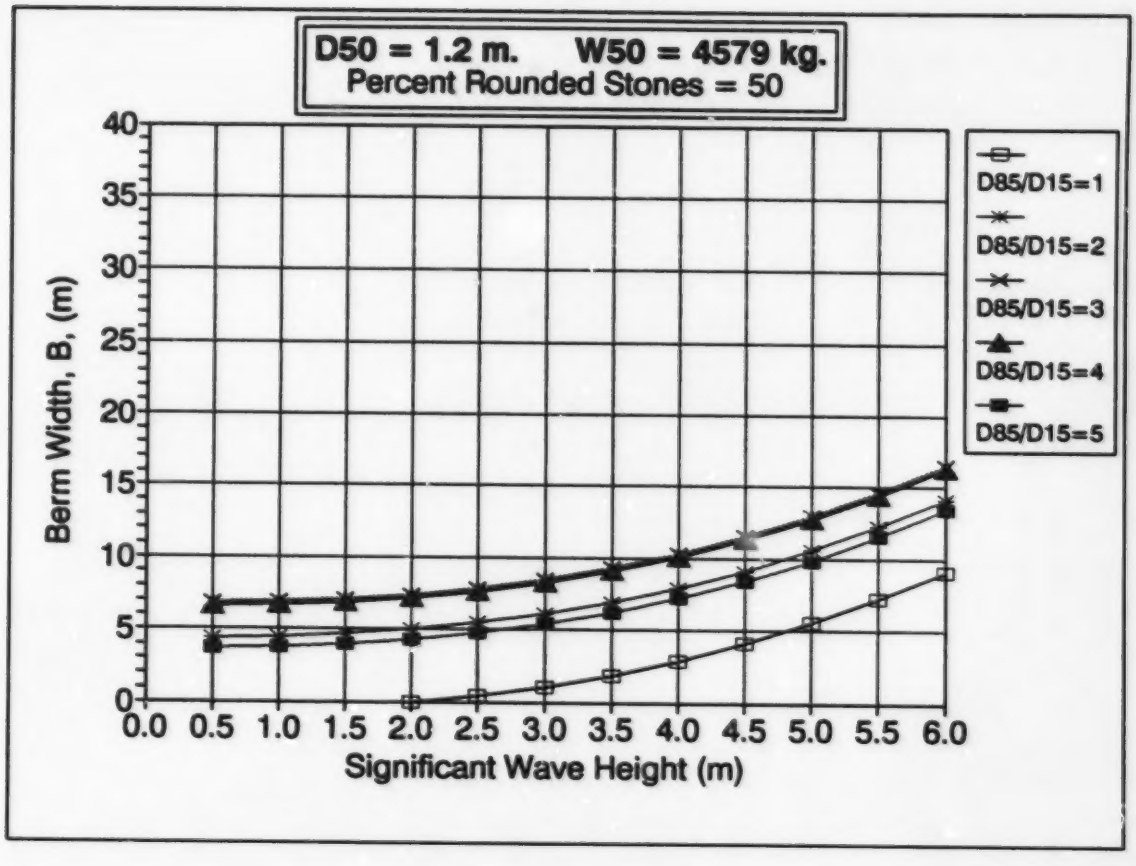

D50 = 0.7 m. W50 = 909 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

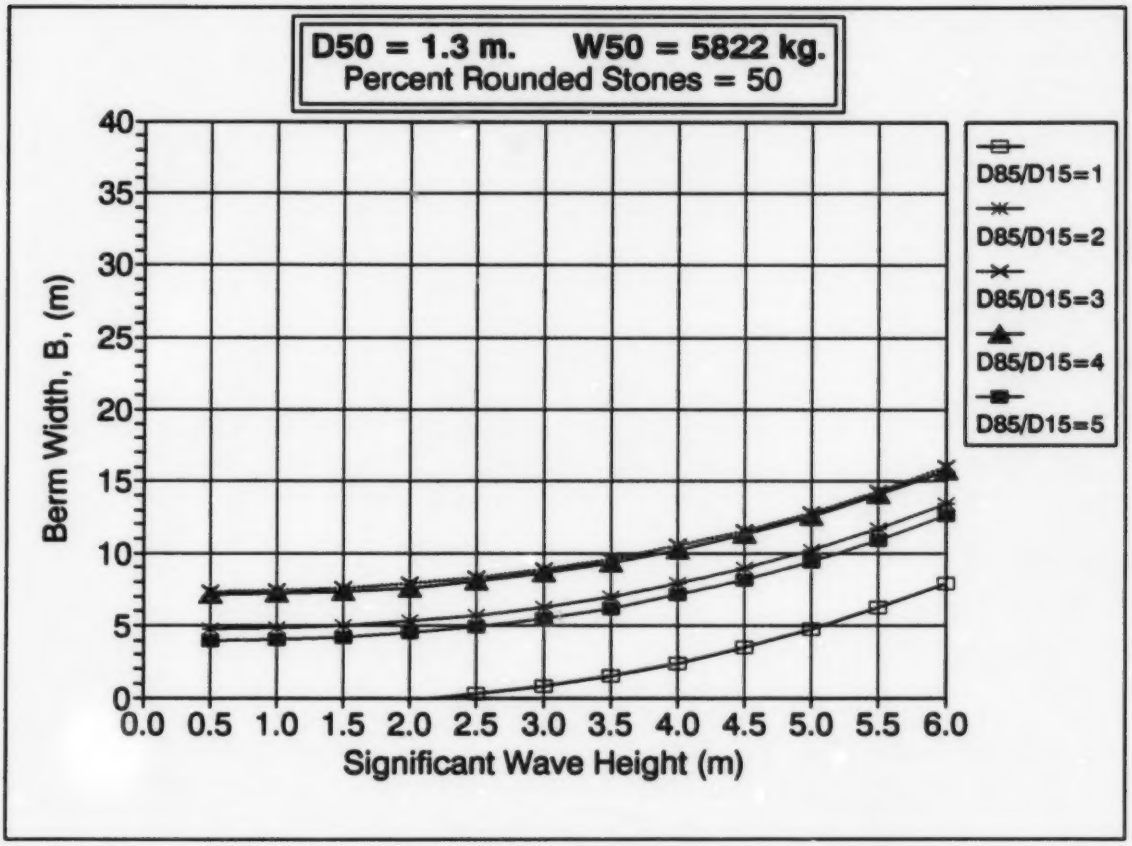

D50 = 0.8 m. W50 = 1357 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

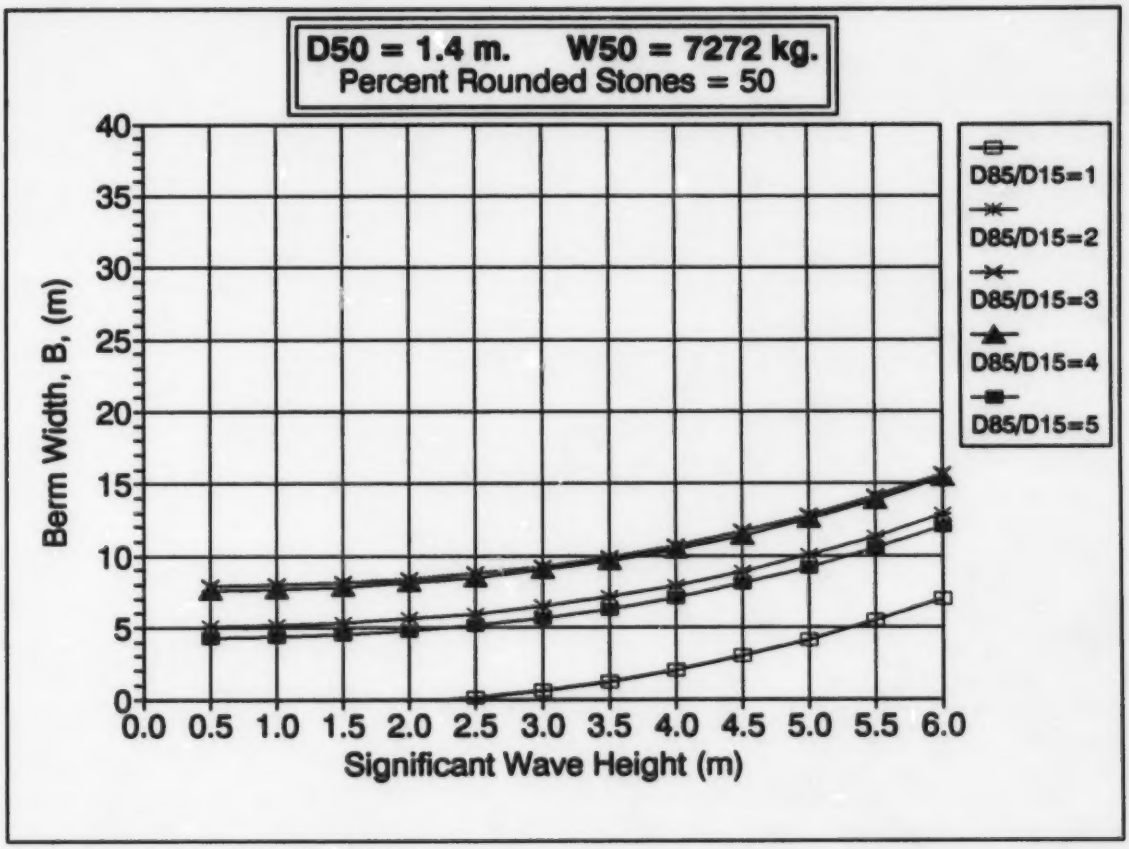

D50 = 0.9 m. W50 = 1932 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

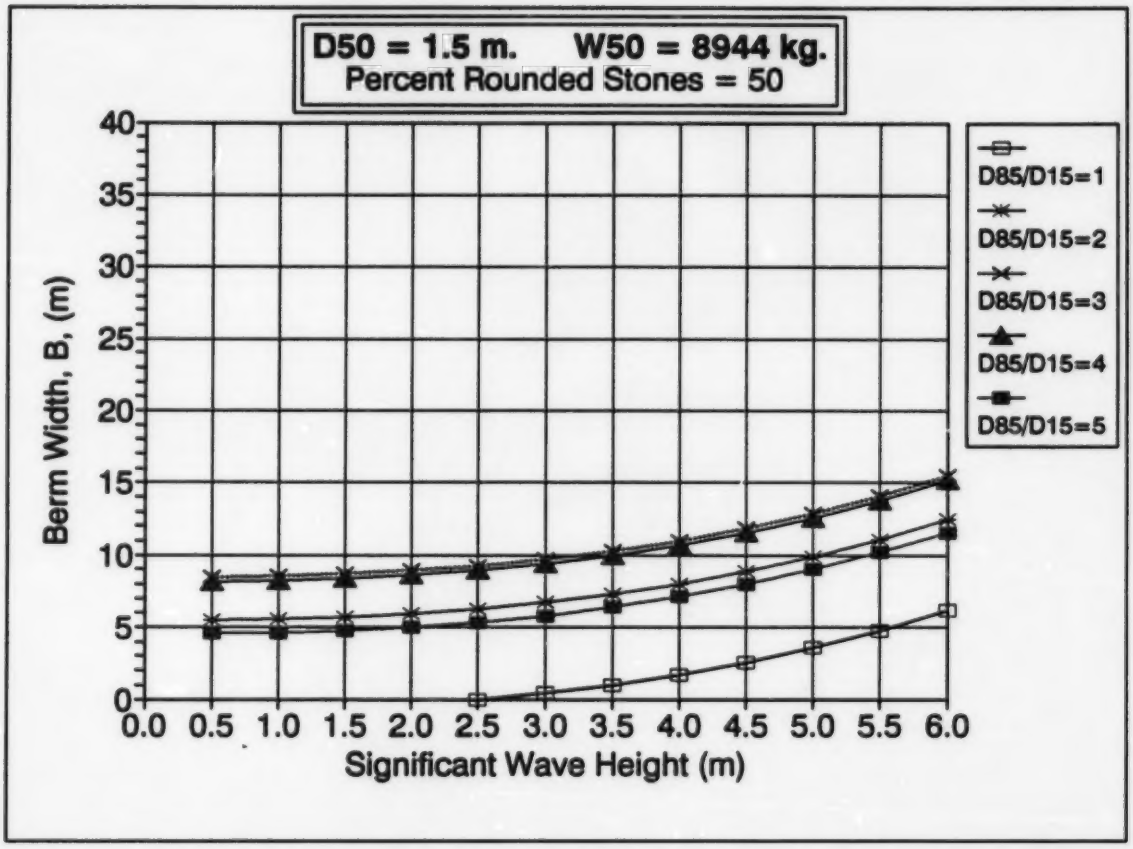

D50 = 1.0 m. W50 = 2650 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

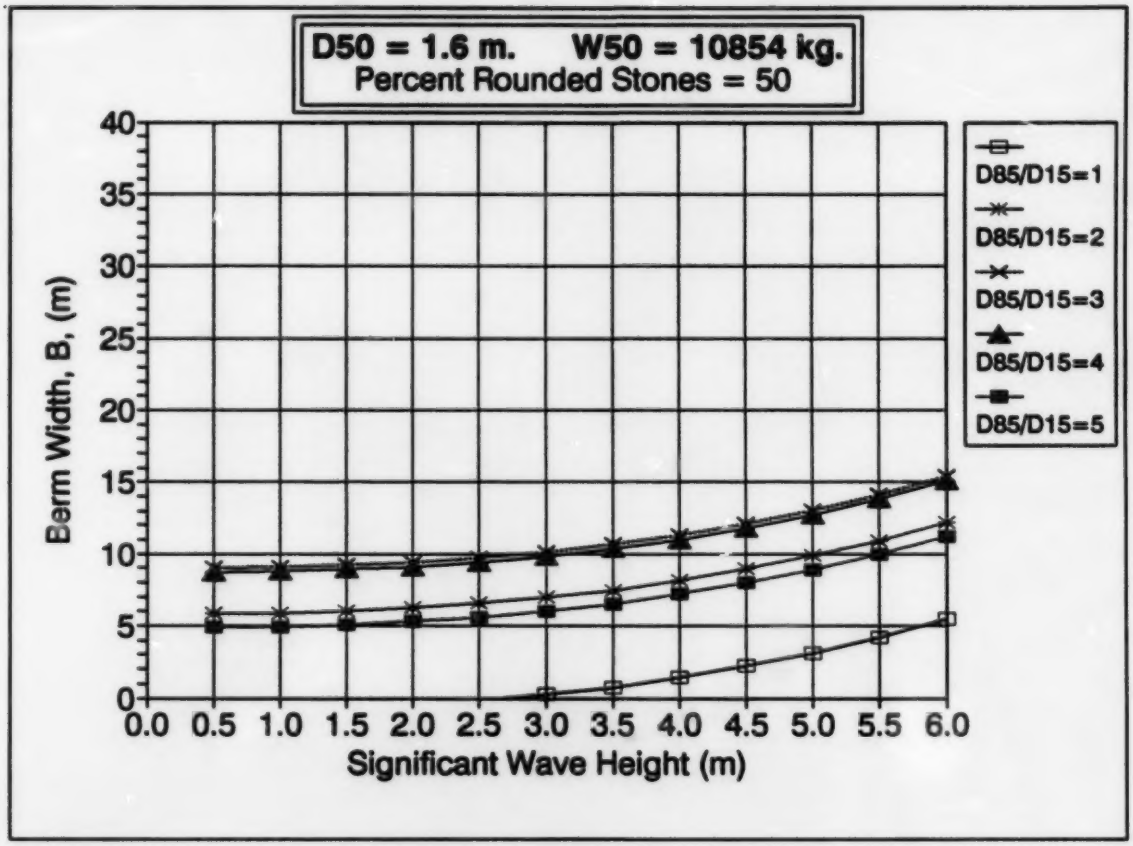

D50 = 1.1 m. W50 = 3527 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

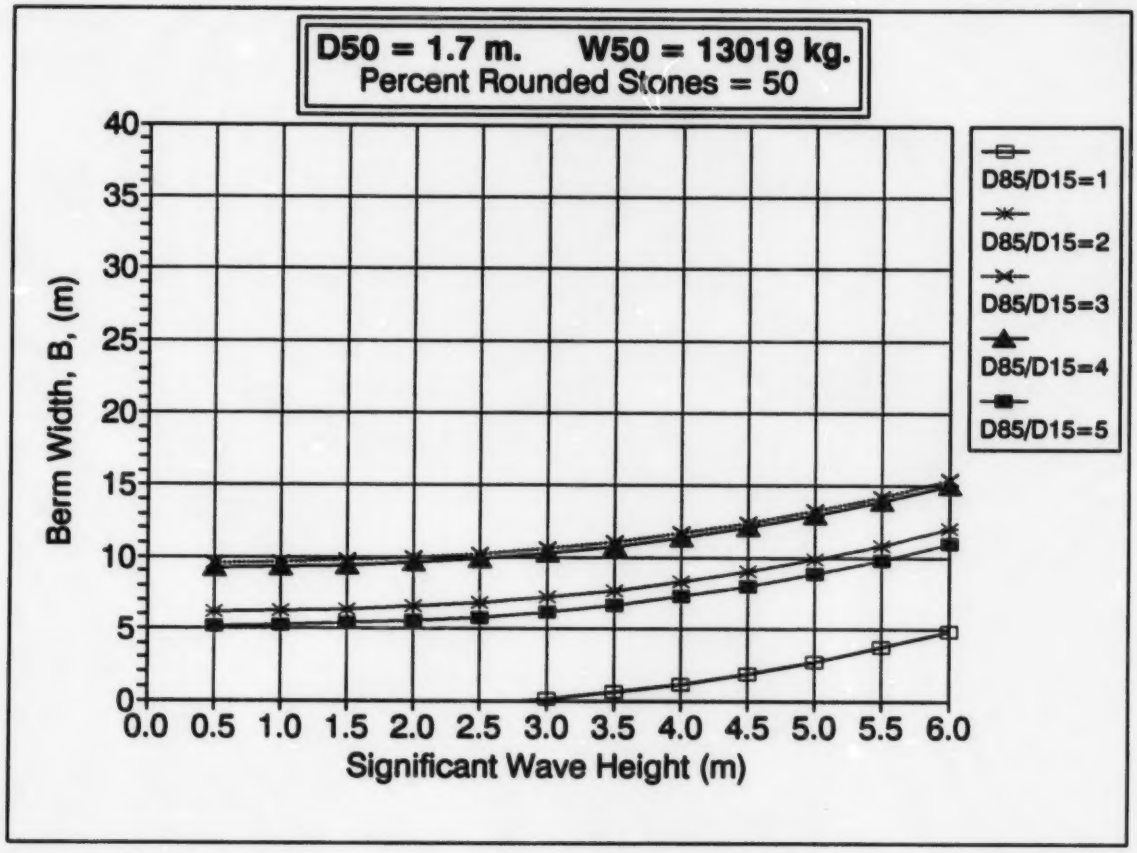

D50 = 1.2 m. W50 = 4579 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
Significant Wave Height (m)
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

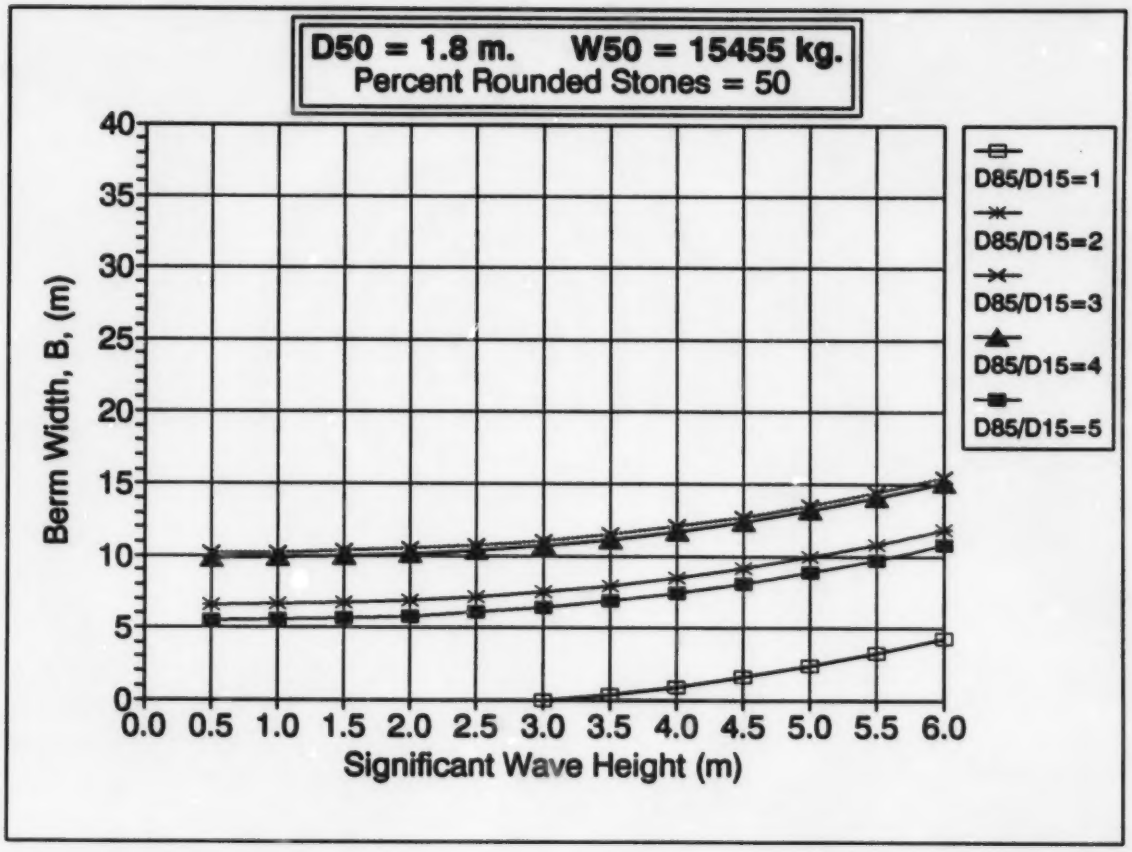

D50 = 1.3 m. W50 = 5822 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

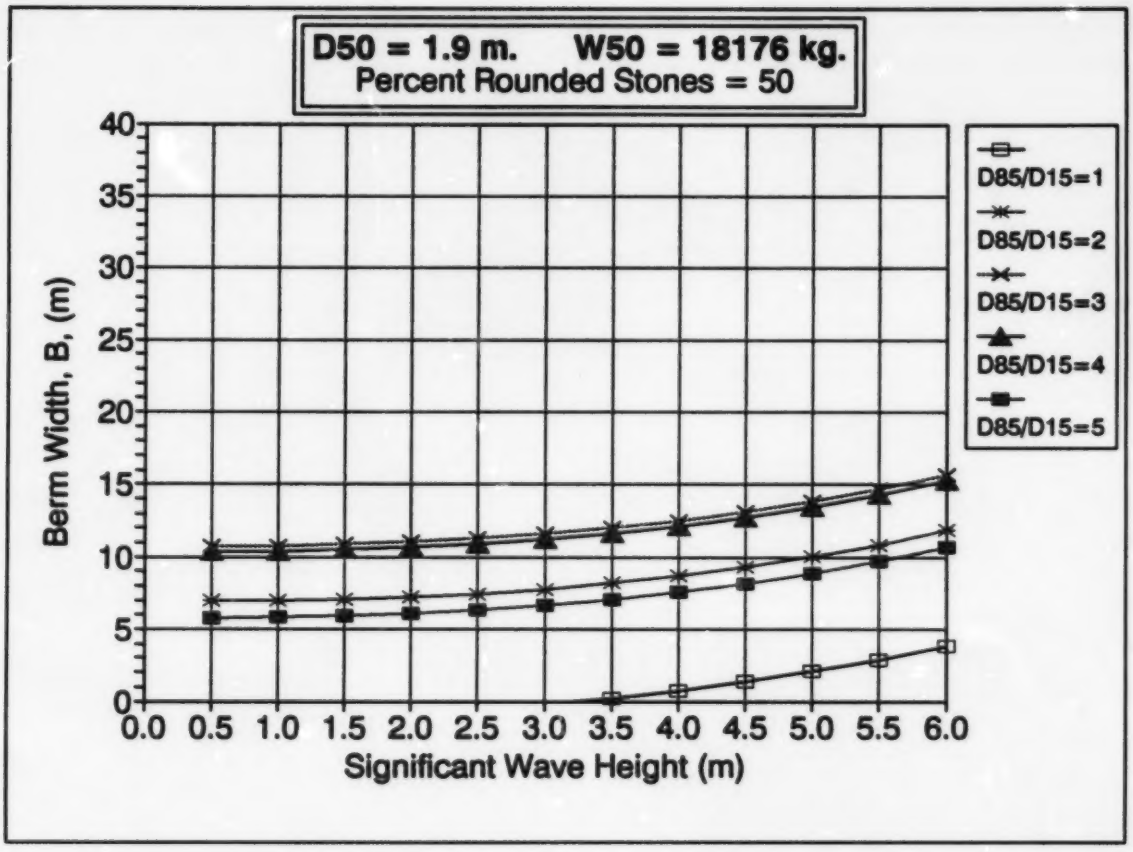

D50 = 1.4 m. W50 = 7272 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5

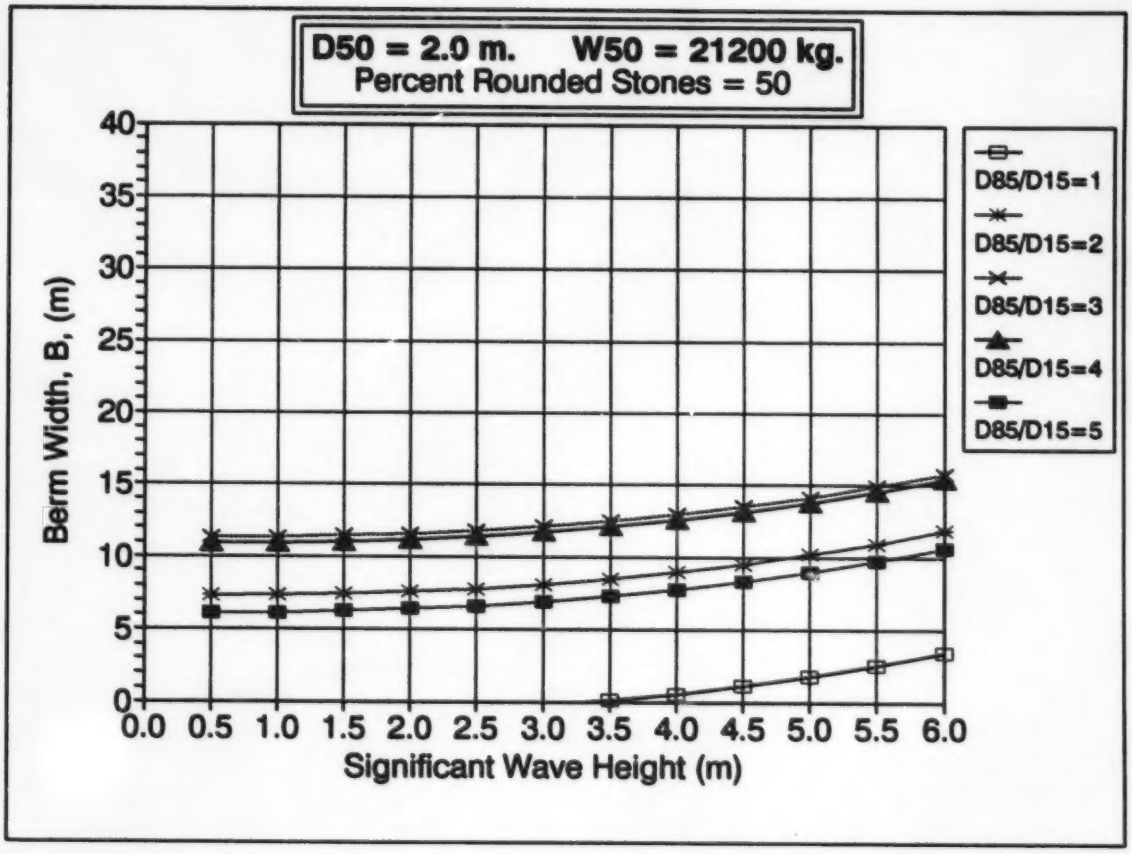

D50 = 1.5 m. W50 = 8944 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.6 m. W50 = 10854 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.7 m. W50 = 13019 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.8 m. W50 = 15455 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 1.9 m. W50 = 18176 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5


D50 = 2.0 m. W50 = 21200 kg.
Percent Rounded Stones = 50
Berm Width, B, (m)
Significant Wave Height (m)
0
5
10
15
20
25
30
35
40
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
D85/D15=1
D85/D15=2
D85/D15=3
D85/D15=4
D85/D15=5